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FUNCTIONAL DESCRIPTION OF HELICOPTER AUTOMATIC TURN COORDINATION SYSTEMS

RICHARD WALCHLI

Bunker-Ramo Corporation

TECHNICAL REPORT AFFDL-TR-69-70

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FUNCTIONAL DESCRIPTION OF HELICOPTER AUTOMATIC TURN COORDINATION SYSTEMS

RICHARD WALCHLI

Bunker-Ramo Corporation

FOREWORD

This report represents an effort to compile under a single cover (1) a functional description of the automatic turn coordination system concept developed by Mr. Knemeyer, USAF Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, and (2) to document differences in the functioning and mode-switching logic of three developmental systems that have been installed and tested in a ground-based hover simulator, a Hughes 300 helicopter and a Sikorsky CH-3C helicopter.

This report was prepared as a part of an Air Force advanced development program entitled "VTOL Integrated Flight Control System," Program Structure 698DC. This program has been under the direction of the Flight Control Division of the Air Force Flight Dynamics Laboratory (AFFDL) Research and Technology Division. This report was prepared by The Bunker-Ramo Corporation, Defense Systems Division, Canoga Park, California, under subcontract A87966s, "Human Engineering Support VTOL Program," to Lear Siegler, Inc., Astronics Division, Santa Monica, California, as a part of Air Force Contract AF33(615)-5101, "VTOL Control-Display Criteria Development."

The author wishes to acknowledge the following individuals for their contribution toward supplying the information upon which this report is based: Mr. Frank Mahoney, Lear Siegler, Inc., Mr. Harold Goff, Consultant to Lear Siegler, Inc., for data relevant to the H-300 system; Mr. Arthur Kozik and Mr. J. Miller, Lear Siegler, Inc., for data relevant to the CH-3C system; and Mr. W. Williamson, Singer-General Precision, Inc., Link Group for data relevant to the ground-based hover simulator system.

This Technical Report has been reviewed and is approved.

Loren A. Anderson

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ABSTRACT

An analysis was made of the automatic turn coordination systems installed in the helicopter simulator, the H-300, and the CH-3C helicopters to determine the nature of the differences in mode-switching logic between the three installations. The data was obtained from the cognizant design engineers of each project and summarized in this report. Logic flow diagrams of each of the three systems were constructed to indicate the mode switching resulting from changes in airspeed, attitude, and rudder force application. Comparisons of the diagrams indicate differences in the system mode-switching logic.

This abstract is subject to export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Flight Dynamics Laboratory (FDCR), Wright-Patterson AFB, Ohio 45433.

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INTRODUCTION

The Air Force VTOL Advanced Development Program, 698DC, is a program aimed at developing and demonstrating the technology required to provide the pilot with a manual capability of flying a VTOL aircraft on instruments throughout its mission profile. Because of the inherent instability characteristics typical of VTOL aircraft, the demands placed upon the pilot are significantly increased over that of a fixed-wing aircraft, even during VFR flight. The nature of these control and display demands under conditions of IFR flight have not been explored in flight.

Because of the state-of-the-art of VTOL airframe development, a Hughes H-300, a Sikorsky CH-3C helicopter, and a ground-based helicopter simulator were selected as the research tools for the development of control concepts directed at eliminating these inherent problems. The simulator has been used as an engineering tool to provide preliminary checks on the feasibility of design concepts. The H-300 has been used to gain initial flight experience with the concepts that were previously developed on the simulator, and the CH-3C has served as a test bed for further development and refinements of the concepts in a vehicle having greater mass and dynamics closer to those of a VTOL aircraft than exist in the light, highly responsive H-300.

At the onset, it was apparent that a basic shortcoming of the helicopter as a VTOL simulator is manifested in the complexity of the yaw axis control task. Design effort was therefore undertaken to develop a "yaw axis augmentation system" and to incorporate automatic turn coordination capabilities in its design so that the helicopter could be made into a more efficient VTOL simulator.

The fundamental philosophy underlying the design of control stabilization for VTOL aircraft has been the Pilot Manager concept. This concept requires that the supporting automatic control subsystem assist the pilot in the way that the pilot would fly the aircraft, without infringing upon his command prerogatives. The immediate result is to free the pilot from the performance of routine yet time-consuming control and stabilization subfunctions that can be

performed efficiently by automatic devices. The concept provides for the pilot to constantly retain absolute command over all control functions, exercising his judgment and intelligence as a manager of the entire system. The design of the lateral control subsystem developed as a part of ADP 698DC encompasses this pilot manager concept. The systems, whose operational functions are described here, provide for yaw stabilization, turn coordination, and lateral translation. Working through the conventional rudder pedals, the stability augmentation system provides for (1) pilot command inputs, (2) yaw stabilization without the necessity for continuous pilot control (as well as the routine yet demanding task of maintaining vehicle heading), (3) automatic turn coordination, and (4) a simple method for lateral translation at low forward airspeeds.

A significant factor in the workload of a helicopter pilot is the relative complexity of the yaw axis control task. For both steady state and maneuvering flight he must constantly remain active in the yaw axis control loop since every control action results either in a change in engine torque or cross coupling into yaw. Basic stabilization systems have been found to assist in unburdening the pilot's control task. However, the task remains considerably more complex than its counterpart in a fixed-wing aircraft because of the lack of basic aerodynamic stability of the helicopter. The turn coordination system relieves this problem by not only providing control signals to aid in accomplishing coordinated turns and heading stabilized lateral translation maneuvers, but also by incorporating mode-switching logic to assist the pilot in executing the appropriate maneuver for the airspeed regime in which he is operating. The net result is significant unburdening without compromising pilot command authority. The unburdening is apparent in reductions in pilot control activity in the yaw axis and simplification of related mental tasks associated with selection of the appropriate maneuvering mode.

The turn coordination features of the stability augmentation system have been installed and tested in each of the three research vehicles. Although the basic design concept has been consistent for each of the installations, differences in the vehicles, as well as the consequence of involving different designers in the design of the three installations, has resulted in design modifications as

the development has progressed. As a result of these design differences, functional differences exist between the three installations. It is the purpose of this report to provide under one cover a functional description of the basic concept and of each turn coordination system. Differences that exist in their functioning have then been identified.

PRINCIPLES OF OPERATION OF THE TURN COORDINATION COMPUTER

The yaw axis stabilization system employs a unique application of a conventional servo control technique. Figure 1 shows a schematic of a representative installation employing the yaw axis control system concepts under development. A servo is used to position the yaw mechanism under the control of the pilot and airborne sensors. The pilot commands are transmitted to the servo by a force sensor mounted in the pedal linkages; and application of force is transmitted to the switching logic which determines the mode of operation desired by the pilot. If there is no force on the pedals, the vehicle is directionally stabilized. With force exerted on the pedals, a yaw rate is established proportional to the pedal force. When force is removed, the vehicle becomes stabilized on the direction which was attained at the instant the force was removed.

The turn coordination computer provides a yaw rate command signal for use in a helicopter of VTOL stabilization system for automatic coordinated turn execution. The computed yaw rate command is directly proportional to the angle of bank and inversely proportional to the aircraft velocity. The computational equation for the yaw rate command signal (r_c) is:

$$r_c = \frac{g \sin \phi}{V}$$

where ϕ is bank angle and V is airspeed. Thus, turn coordination signals are provided only during banked attitude conditions.

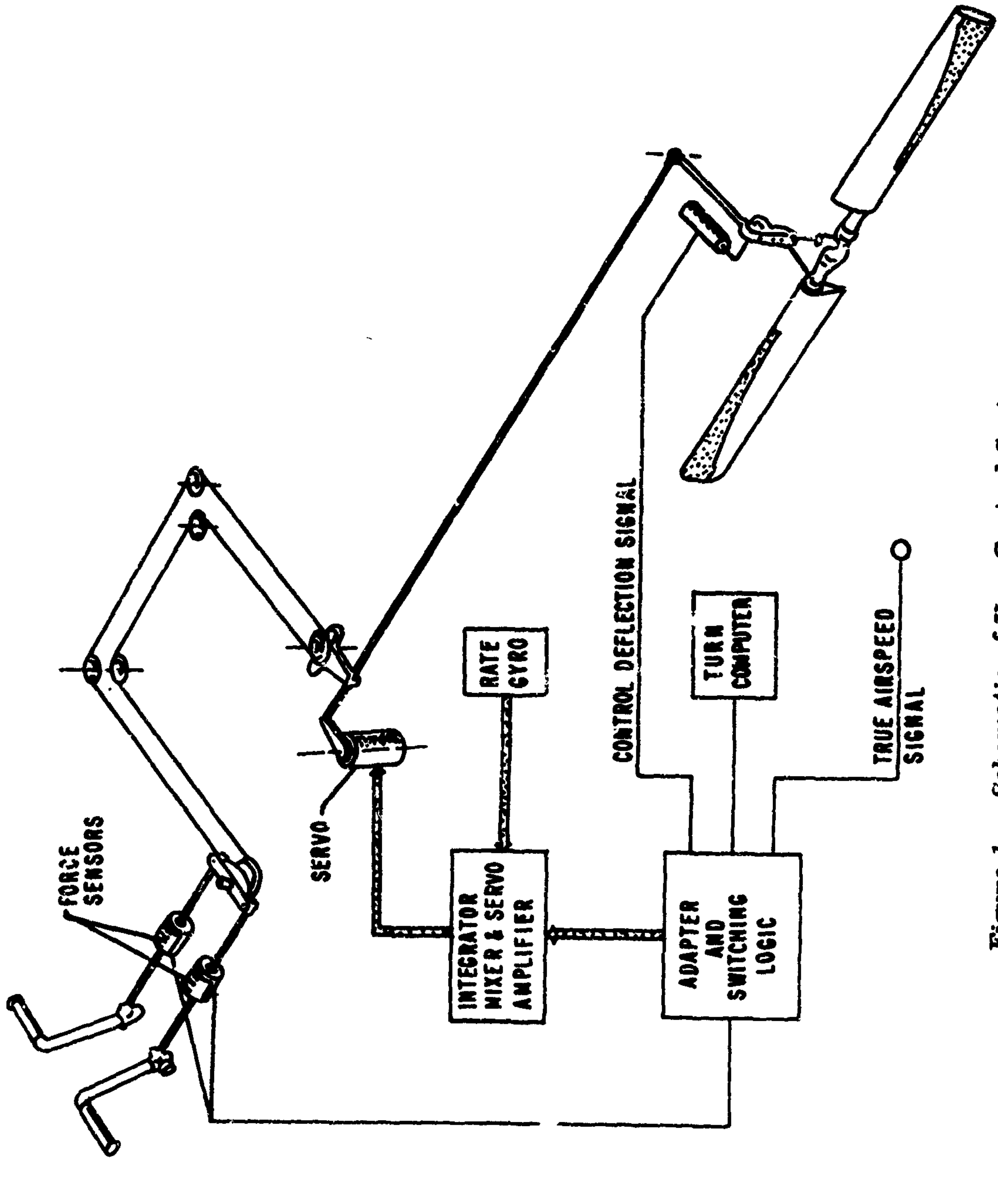


Figure 1. Schematic of Yaw Control System

Control logic is included to provide the pilot with the option of selecting the following operational modes, within the constraints imposed by the additional switching logic described in the following paragraph.

1. Automatic turn coordination
2. Directionally stabilized lateral translation.
3. Directionally stabilized mode

In addition to the control logic for pilot selection of operating mode, additional logic is provided for supporting the pilot in the way that he normally flies a helicopter. For example, at high speeds where lateral translations are not likely to be desired, the turn coordination signal is automatically provided without the need for the pilot to select this mode. Three airspeed regimes have been defined for the basis of the automatic mode-switching characteristics of the turn coordination computer. These are:

1. Hover Regime: hover to high taxi (V_1).
2. High Taxi Regime: High taxi (V_1) to normal cruise (V_u).
3. Cruise Regime: Normal cruise (V_u) to maximum airspeed capable.

No automatic turn coordination assistance is provided for airspeeds in the hover regime (i.e., less than V_1), since at these low speeds exceedingly high yaw rates would be commanded as a result of the inverse relationship of airspeed in the basic equation for the yaw rate command. It is also in the hover regime where lateral translations or horizontal yaw changes are normally desired.

For airspeeds in the high taxi regime (i.e., speeds between V_1 and V_u), either automatic turn coordination or directionally stabilized lateral translation is possible, the choice being dependent upon the expressed intent of the pilot. Pilot intent is expressed by momentary application of a rudder force in a manner that is natural for the particular maneuver being executed. For example, if a coordinated turn is the desired maneuver, the pilot would express his intent to the system by momentarily applying a rudder pedal force in the same direction as the desired maneuver. If, however, a directionally stabilized lateral translation is desired, the pilot's intent would be expressed to the system by momentarily applying a rudder pedal force in the direction opposite

the direction of bank. Thus the initial actions of the pilot in selecting automatic turn coordination or directionally stabilized lateral translation are "natural" in that the actions required to express his intent to the automatic system are similar to the initial actions that are required in the absence of the stability system.

For airspeeds in the cruise regime the turn coordination command signal is automatically provided at any time the bank angle exceeds a prescribed bank angle threshold. To accomplish a lateral translation at airspeeds in the cruise regime, the pilot must constantly oppose the turn coordination command signal with rudder pedal force opposite the direction of bank. Table I summarizes the modes of operation of the yaw axis augmentation system.

FUNCTIONAL DESCRIPTION, GENERAL

A functional description of the yaw axis augmentation systems as implemented in each of the three research vehicles is included in the following sections. These descriptions summarize the basic mode-switching logic of the yaw axis augmentation system of each vehicle. In addition to the functional descriptions, logic flow diagrams for each system are included in the appendix. The logic flow diagrams may be used to determine the effects of the mode switching resulting from either a change in pilot intent as expressed by application of rudder forces, or a change in airspeed or roll attitude during aircraft maneuvering. Each diagram shows the effects of the mode switching in terms of the maneuver that will result when changes in one or more of the following parameters occur:

1. Airspeed
2. Bank angle
3. Rudder pedal force

In addition, direction and duration of rudder pedal forces are considered.

TABLE I

YAW AXIS DESIGN CONCEPT OPERATIONAL MODE SUMMARY

OPERATIONAL MODE	SPEED REGIME		
	Hover ($TAS < V_1$)	High Taxi ($V_1 < TAS < V_u$)	Cruise ($TAS > V_u$)
Automatic Coordinated Turn	None	When pilot intent is expressed by application of rudder force in direction of bank.	When bank angle exceeds bank angle threshold.
Directionally Stabilized Lateral Translation	When roll attitude deviates from wing level.	When pilot intent is expressed by application of rudder force in direction opposite bank angle.	None (Lateral translation possible by overriding turn coordination command signal).
Directionally Stabilized Mode	When roll attitude is wing level. Yaw rate is proportional to rudder pedal force.	When bank angle is less than bank angle threshold. Yaw rate is proportional to rudder pedal force.	When bank angle is less than bank angle threshold. Yaw rate is proportional to rudder force.

Since the mode-switching logic is dependent upon the airspeed regime as well as on the mode of operation existing at the time of a change in pilot intent, or in one or more of the above listed parameters, three diagrams are given for each of the systems in the appendices. Each diagram shows the effects of the changes as related to a predefined initial condition or operating mode. The initial conditions represented in the logic diagrams are:

1. Directionally Stabilized Mode with airspeed in the high taxi regime. In the directionally stabilized mode, roll attitude is level, aircraft heading is automatically stabilized, and yaw rates can be commanded by the pilot in proportion to the applied rudder forces.
2. Directionally Stabilized Lateral Translation Mode with airspeed in the high taxi regime. In the directionally stabilized lateral translation mode the aircraft is in a banked attitude, translating horizontally in the direction of bank with aircraft heading stabilized on the heading that exists at the moment rudder pedal forces are released.
3. Automatic Turn Coordination Mode with the airspeed in the high taxi regime. In this mode of operation, the aircraft will execute a coordinated turn while in a banked attitude. Yaw axis command signals appropriate for maintaining a coordinated turn are automatically provided by the turn coordination computer. No rudder pedal forces are required during an automatically coordinated turn.

Specific differences in the functioning of the three systems are discussed in the last section of this report and can be noted by comparison of the logic flow diagrams for each system.

HELICOPTER SIMULATOR TURN COORDINATION SYSTEM

With the yaw axis stabilization system and turn coordination computer activated, system function is as described in the following paragraphs. For the directionally stabilized mode, the system produces a yaw rate proportional to the amount of pedal force exerted by the pilot. The yaw stabilization system provides for heading stabilization during wing level flight upon the existing

heading when no pedal force is applied. Introduction of a roll attitude from wings level with application of rudder pedal force will result in either directionally stabilized lateral translation or an automatic coordinated turn, the result being dependent upon the values of

1. The airspeed
2. The magnitude of the pedal force
3. The direction of the pedal force, i.e., same or opposite rudder as bank angle
4. The duration of the pedal force, and
5. The magnitude of the bank angle

Hover Regime (TAS less than 10 mph)

For airspeeds less than 5 mph, no automatic turn coordination signal is provided. For airspeeds less than 10 mph, an automatic turn coordination signal is provided only when an automatically coordinated turn has been executed at a speed in the high taxi regime and the airspeed has been allowed to decrease into the hover regime. In such a case the turn coordination signal is washed out from 10 mph to 5 mph. This logic is provided to prevent undesirable transients due to mode switching when operating at speeds close to the 10 mph upper limit of the hover regime. In all other cases when operating in the hover regime, yaw rates proportional to the rudder pedal forces will result, and directionally stabilized lateral translation will result with introduction of a bank angle in the absence of rudder pedal forces.

High Taxi Regime (TAS greater then 10 mph and less than 40 mph)

While operating in the high taxi regime, introduction of a bank angle from level flight will result in an automatic coordinated turn when:

1. The bank angle attitude exceeds a bank angle threshold (1.05 degrees) and
2. A pedal force in the direction of the bank greater than a predetermined rudder force threshold is applied

Once the automatic turn coordination signal is engaged, further application of rudder pedal force by the pilot is unnecessary to maintain the coordinated turn. Rolling to a level roll attitude (i.e., bank angle less than 1.05 degrees) will automatically result in switching modes from automatic turn coordination

to directional stabilization. If the pilot desires to change from an automatic coordinated turn to a directionally stabilized lateral translation while operating in the high taxi regime, without rolling to a level roll attitude, he may do so by applying a rudder pedal force opposite the direction of turn and holding this force for at least three seconds. Once the mode switching has occurred, further application of rudder force is not required. To reengage the automatic turn coordination feature, the pilot need only apply a rudder pedal force greater than the force threshold in the direction of the bank. Again, after holding this force for three seconds, further application of rudder force is unnecessary since the automatic turn coordination signal will be engaged. Introducing a bank angle from level flight without application of rudder pedal forces results in a directionally stabilized lateral translation, since the automatic turn coordination signal will not be engaged due to the absence of the appropriate rudder pedal force.

Cruise Regime (TAS greater than 40 mph)

For airspeeds greater than 40 mph, directional stabilization is provided when the bank angle does not exceed the bank angle threshold. When bank angles greater than the threshold are entered, the yaw signal appropriate for maintaining a coordinated turn is automatically provided by the turn coordination computer. In the cruise regime no pedal forces are needed to execute an automatically coordinated turn. The yaw axis control system in the helicopter simulator does not provide for directionally stabilized lateral translation in the cruise regime. To accomplish a lateral translation in the cruise regime, the automatic turn coordination system must be deactivated and the maneuver accomplished under manual control by the pilot.

Table II summarized the operating modes within each of the three airspeed regimes. In addition to the basic operating modes shown in this table, switching logic is included to minimize or eliminate transients resulting from acceleration or deceleration between airspeed regimes. A functional description of system operation as related to airspeed changes is discussed in the following paragraph. The logic flow diagrams in the appendix describe in detail the functioning of the yaw axis system switching logic.

TABLE II

YAW AXIS OPERATIONAL MODE SUMMARY. HOVER SIMULATOR

OPERATIONAL MODE	SPEED REGIME		
	Hover (0 - 10)	High Taxi (10+ - 40)	Cruise (40+ - Max)
Automatic Coordinated Turn	None	When pilot intent is expressed by application of rudder pedal force in direction of bank.	When bank angle exceeds bank angle threshold.
Directionally Stabilized Lateral Translation	When roll attitude deviates from wing level.	When bank is entered and no rudder pedal force applied.	None (Lateral translation possible by deactivating turn coordination computer).
Directionally Stabilized Mode	When roll attitude is wing level. Yaw rate proportional to rudder pedal force.	When bank angle is less than bank angle threshold. Yaw rate is proportional to rudder pedal force.	When bank angle is less than bank angle threshold. Yaw rate is proportional to rudder pedal force.

Mode Changes due to Increasing or Decreasing Airspeed

Since no automatic turn coordination signal is provided when a bank is entered in the hover regime, acceleration with no rudder pedal forces applied while in a banked attitude from an airspeed within the hover regime into the high taxi regime will result in a continuation of the directionally stabilized lateral translation maneuver until the cruise regime is entered. Upon entering the cruise regime while performing a directionally stabilized lateral translation, the system will switch modes to automatic turn coordination. If the simulator decelerates from the cruise regime while in a banked attitude, the automatic turn coordination signal is provided throughout the deceleration through the high taxi regime and into the hover regime. As the speed decreases into the hover regime, the turn coordination signal is washed out to zero signal at 5 mph. Deceleration from speeds within the high taxi regime while executing a directionally stabilized lateral translation results in a continuation of this mode of operation through all speeds to hover.

H-300 TURN COORDINATION SYSTEM

The yaw axis stabilization system and turn coordination computer installed in the H-300 provides for the three basic operational modes, i.e., automatic turn coordination, directionally stabilized lateral translation, and directionally stabilized wings level flight. Each mode is available over the airspeed range of the H-300 with the exception of heading stabilized lateral translation, which is restricted to the hover and high taxi airspeed regimes, and automatic coordinated turning, which is excluded from the hover regime. Introduction of a bank angle from wing level with application of rudder pedal force will result in either directionally stabilized lateral translation or an automatic coordinated turn, the result being dependent upon the values of

1. The airspeed
2. The magnitude of the pedal force
3. The direction of the pedal force
4. The duration of the pedal force
5. The magnitude of the bank angle.

Hover Regime (TAS less than 12 mph)

For airspeeds in the hover regime, heading is automatically stabilized when no rudder pedal forces are applied. Application of rudder pedal forces results in yaw rates proportional to these forces. No automatic turn coordination signal is provided in the hover regime. Thus, introduction of a bank angle without rudder pedal forces automatically results in a directionally stabilized lateral translation maneuver. If a coordinated turn is desired during operation in the hover regime, the pilot must manually coordinate the turn by applying appropriate rudder pedal forces.

High Taxi Regime (TAS greater than 12 mph and less than 26 mph)

While operating in the high taxi regime, introduction of a bank angle from level flight will result in an automatic coordinated turn when:

1. The bank angle exceeds a bank angle threshold (5 degrees),
2. A rudder pedal force in the direction of the bank greater than a predetermined rudder force threshold is applied, and
3. The rudder pedal force is applied for at least three seconds.

Once engaged in the automatic turn coordination mode, further application of rudder force is not required to continue the coordinated turning maneuver. Rolling to a level roll attitude (i.e., bank angle less than 3 degrees) will automatically result in a mode switching from automatic turn coordination to directionally stabilized level flight. If the pilot desires to change from an automatically coordinated turn to a directionally stabilized lateral translation without rolling to wings level to disengage the coordination signal, he may do so by applying a rudder pedal force greater than the rudder force threshold in the direction opposite the direction of the turn. When this rudder pedal force has been applied for three seconds, the result will be a change in the operating mode from automatic coordinated turning to directionally stabilized lateral translation. To enter a heading stabilized lateral translation from level flight, the pilot need only introduce a bank angle without the application of rudder pedal forces.

Cruise Regime (TAS greater than 26 mph)

When operating in the cruise regime, the vehicle is directionally stabilized when the bank angle is less than the bank angle threshold. As in the hover and

high taxi regimes, application of rudder pedal forces while in the directionally stabilized flight mode results in yaw rates proportional to the applied rudder pedal forces. Introduction of a bank angle greater than the bank angle threshold without the application of rudder pedal forces results in a mode switching to automatic turn coordination. Anytime the bank angle is greater than the bank angle threshold, the automatic turn coordination signal is provided. Therefore, directionally stabilized lateral translation is not possible in the cruise regime. To accomplish a lateral translation, the pilot must apply a continuous rudder pedal force opposite the direction of the turn. The rudder force signal will thus be of an opposite polarity to the turn coordination signal that is provided by the turn coordination computer. The resultant yaw rate will be proportional to the algebraic sum of these two signals. Thus to accomplish a lateral translation in the cruise regime, the pilot must introduce rudder pedal forces which are sufficient to produce a pedal force signal that, when summed with the turn coordination signal, will result in the yaw rate appropriate for the desired maneuver. A summary of the basic operating modes within each of the three airspeed regimes is shown in Table III. The logic flow diagrams in the Appendix describe in detail the functioning of the yaw axis switching logic in the H-300.

Mode Changes due to Increasing or Decreasing Airspeed

In the hover and high taxi regimes, the conditions that must be satisfied and the order in which they must be satisfied to accomplish a switching of modes from directional stabilization or directionally stabilized lateral translation to automatic turn coordination are:

1. The airspeed must exceed the upper limit of the hover regime (12 mph).
2. The bank angle must exceed the bank angle threshold (3 degrees).
3. The rudder pedal force in the direction of the bank must exceed the rudder force threshold, and
4. The rudder pedal force must be applied for at least three seconds.

In the cruise regime, conditions (3) and (4) need not be satisfied to engage the automatic turn coordination mode. However, additional control logic is included to prevent undesirable transients caused by mode switching that would occur when accelerations or decelerations result in entering a new airspeed operating regime. If for example, the directionally stabilized lateral translation mode is engaged during operation in the high taxi regime and the airspeed is increased

TABLE III

YAW AXIS OPERATIONAL MODE SUMMARY, H-300

OPERATIONAL MODE	SPEED REGIME		
	Hover (0 - 12 mph)	High Taxi (12+ - 26 mph)	Cruise (26+ - Max)
Automatic Coordinated Turn	None	When pilot intent is expressed by application of rudder pedal force for 3 seconds in direction of bank.	When bank angle exceeds bank angle threshold.
Directionally Stabilized Lateral Translation	When roll attitude deviates from wing level.	When bank is entered and no rudder pedal force applied.	None. (Directionally Stabilized Lateral Translation possible only if in this mode prior to entering cruise regime.)
Directionally Stabilized Mode	When roll attitude is wing level. Yaw rate proportional to rudder pedal force.	When bank angle is less than bank angle threshold. Yaw rate is proportional to rudder pedal force.	When bank angle is less than bank angle threshold. Yaw rate is proportional to rudder pedal force.

into the cruise regime, the directionally stabilized later-translation mode of operation will continue until the bank angle is reduced to less than the bank angle threshold. Reentering the banked attitude at this same airspeed will result in an automatic coordinated turn because the aircraft is now operating in the cruise regime. If the airspeed is permitted to decrease, no mode changes will occur until the hover regime is entered. As the speed decreases into the hover regime, the operating mode will change from the automatic coordinated turn to directionally stabilized lateral translation.

H-300 System Changes. As noted earlier, the H-300 has been employed to gain initial flight experience with the concepts previously developed and tested in the helicopter simulator. As a result of the initial flight experiences and because of the particular dynamics of the H-300 helicopter, engineering design changes occurred during the developmental testing that resulted in minor differences in the functional operation of the system from that which has been described above. The above description, however, represents the functioning of the basic conceptual design as implemented in the H-300.

One of the changes that was made to explore the utility of the basic concept was the removal of the high taxi speed regime from the switching logic. For this change the speed switch occurred at approximately 25 mph. The result was that, depending upon the airspeed, automatic turn coordination was either provided or not available. Above 25 mph, turn coordination resulted when the bank angle exceeded the threshold value. Below 25 mph, exceeding the bank angle threshold did not engage the turn coordinator, the result being a directionally stabilized lateral translation.

A second change that was made from the basic conceptual design was the result of the dynamics of the H-300. Due to the high torqueing moment of the light H-300 helicopter, a pilot is required to continuously apply a force to but one of the two rudder pedals. To change the direction of the helicopter, the pilot either applies greater pressure to or partially releases the pressure from the rudder pedal, dependent upon whether the pilot desires to change the direction to the right or left of an existing heading. This characteristic of the H-300 dictated that only one rudder pedal force sensor be installed, as opposed to the two required in the simulator or in another helicopter of greater mass.

From the pilots view of the functioning of the system there is little difference in whether the system contained one or two force sensors, since the piloting behavior in executing a directional change would not differ in this particular helicopter. Therefore, since the preceding functional description of the H-300 system assumed two rudder pedal force sensors, it is noted that in fact, the H-300 system utilized but one force sensor.

CH-3C TURN COORDINATION SYSTEM

The yaw axis stabilization system and turn coordination computer installation in the CH-3C provides for three basic operational modes, i.e., automatic turn coordination, directionally stabilized lateral translation, and directionally stabilized level flight. As with the H-300, each mode is available over the airspeed range of the CH-3C with the exception of directionally stabilized lateral translation, which is restricted to the hover and high taxi regimes, and automatic coordinated turning, which is excluded from the hover regime. For level roll attitude conditions, over the entire airspeed range, directional stabilization is provided. Yaw rates proportional to rudder pedal forces can be generated during directionally stabilized flight. Introduction of a bank angle from a level roll attitude will result in either an automatic coordinated turn or a directionally stabilized lateral translation maneuver, the result being dependent upon:

1. The airspeed regime.
2. Whether or not a rudder pedal force is applied, and
3. The direction of the rudder pedal force.

Hover Regime (TAS less than 10 knots)

No automatic turn coordination signal is provided in the hover regime. To accomplish a coordinated turn in this airspeed regime, the pilot must generate the appropriate yaw rate by application of rudder pedal forces in the direction of the turn. Introduction of a bank angle without accompanying rudder pedal forces will result in a directionally stabilized lateral translation in the direction of the bank.

High Taxi Regime (TAS greater than 10 knots but less than 25 knots)

In the high taxi regime introduction of a bank angle greater than the bank angle threshold in the absence of rudder pedal forces results in a switching of modes from that of directional stabilization to automatic turn coordination. If

during an automatically coordinated turn the pilot desires to discontinue the coordinated turn and execute a directionally stabilized lateral translation, he must either (1) roll to a wing level condition and reenter the bank while simultaneously applying a pedal force to the rudder opposite the direction of the bank or (2) continue the bank and apply a rudder pedal force to the rudder opposite the direction of the turn. In either case, the result will be a mode switching to that of heading stabilized lateral translation. As with the [illegible] coordinated turn mode, directionally stabilized lateral translation will continue until the bank angle is reduced to level flight. Once the mode is engaged, further application of rudder pedal forces is unnecessary to continue the maneuver.

Cruise Regime (TAS greater than 25 knots)

When operating in the cruise regime, directional stability is automatically provided when the bank angle is less than the bank angle threshold. As in the hover and high taxi regimes, application of rudder pedal forces while in a directionally stabilized level flight mode results in yaw rates proportional to the applied rudder pedal forces. Introduction of a bank angle greater than the bank angle threshold while operating in the cruise regime will result in an automatic coordinated turn without the application of a rudder force in the direction of the turn. No automatic directionally stabilized lateral translations are possible in the cruise regime. To accomplish a lateral translation in the cruise regime, the pilot must apply rudder pedal forces to the rudder opposite the direction of the turn. As with the H-300, these rudder pedal forces must be of sufficient magnitude and duration to compensate for the turn coordination signal that is automatically provided when the bank angle exceeds the bank angle threshold.

A summary of the basic operating modes within each of the airspeed regimes is shown in Table IV. The logic flow diagrams in the Appendix describe in detail the functioning of the yaw axis switching logic in the CH-3C.

Mode Changes due to Increasing or Decreasing Airspeed

When the aircraft is in a banked attitude in the hover regime, the directionally stabilized lateral translation mode will be engaged. Increasing airspeed into the high taxi regime while maintaining a directionally stabilized lateral translation will result in a continuation of this mode of operation until the speed increases into the cruise regime. When the airspeed increases into the cruise

TABLE IV

YAW AXIS OPERATIONAL MODE SUMMARY, CH-3C

OPERATIONAL MODE	SPEED REGIME		
	Hover (0 - 10 kts)	High Taxi (10+ - 25 kts)	Cruise (25+ -- Max)
Automatic Coordinated Turn	None	When bank angle exceeds threshold. No rudder pedal forces required to engage auto-turn mode.	When bank angle exceeds its threshold.
Directionally Stabilized Lateral Translation	When roll attitude deviates from wing level.	When pilot expresses intent by momentary rudder pedal force in direction of opposite bank.	None. (Lateral translation possible by pilot overriding turn coordination signal with appropriate rudder pedal forces.)
Directionally Stabilized Mode	When roll attitude is level. Yaw rate proportional to rudder pedal forces.	When bank angle is less than bank angle threshold. Yaw rate proportional to rudder pedal forces.	When bank angle is less than bank angle threshold. Yaw rate proportional to rudder pedal forces.

regime while executing a directionally stabilized lateral translation maneuver, the logic provides for automatic mode switching to that of automatic turn coordination as the cruise regime is entered. If the maneuver is that of directionally stabilized lateral translation in the high taxi regime, and the airspeed decreases to the hover regime while maintaining this mode of operation, the directionally stabilized lateral translation maneuver will continue throughout the deceleration. Likewise, if an automatic coordinated turn is being executed while operating in the cruise regime and the airspeed is decreased, no mode switching will occur until the aircraft has decelerated to the hover regime. At this time, the mode will change from automatic turn coordination to directionally stabilized lateral translation.

MAJOR DIFFERENCES BETWEEN SYSTEMS

A variety of differences in system functioning exists between the basic design concept and the three installed systems. Table V, summarizes the major differences that have been identified. This table shows the operational modes within each airspeed regime which would be called for by the basic concept outlined in the first section of this document. Where differences between the conceptual operational functioning and the system functioning occurred, they have been so indicated in this table. Other minor differences between the three systems also exist; however, to simplify the presentation of the more significant differences, the minor differences have not been included in the summary of Table V. A detailed comparison of the logic flow diagrams for each system readily reveals those differences not included in the summary.

The preceding functional descriptions of the three systems considered in this report and comparisons of these systems to identify differences in system functioning reveal several facets of the basic concept that are of significance. It is noted that although differences do exist between the three installations discussed, the basic concept of Pilot Manager persists throughout. In each system certain control and stabilization functions are allocated to automatic

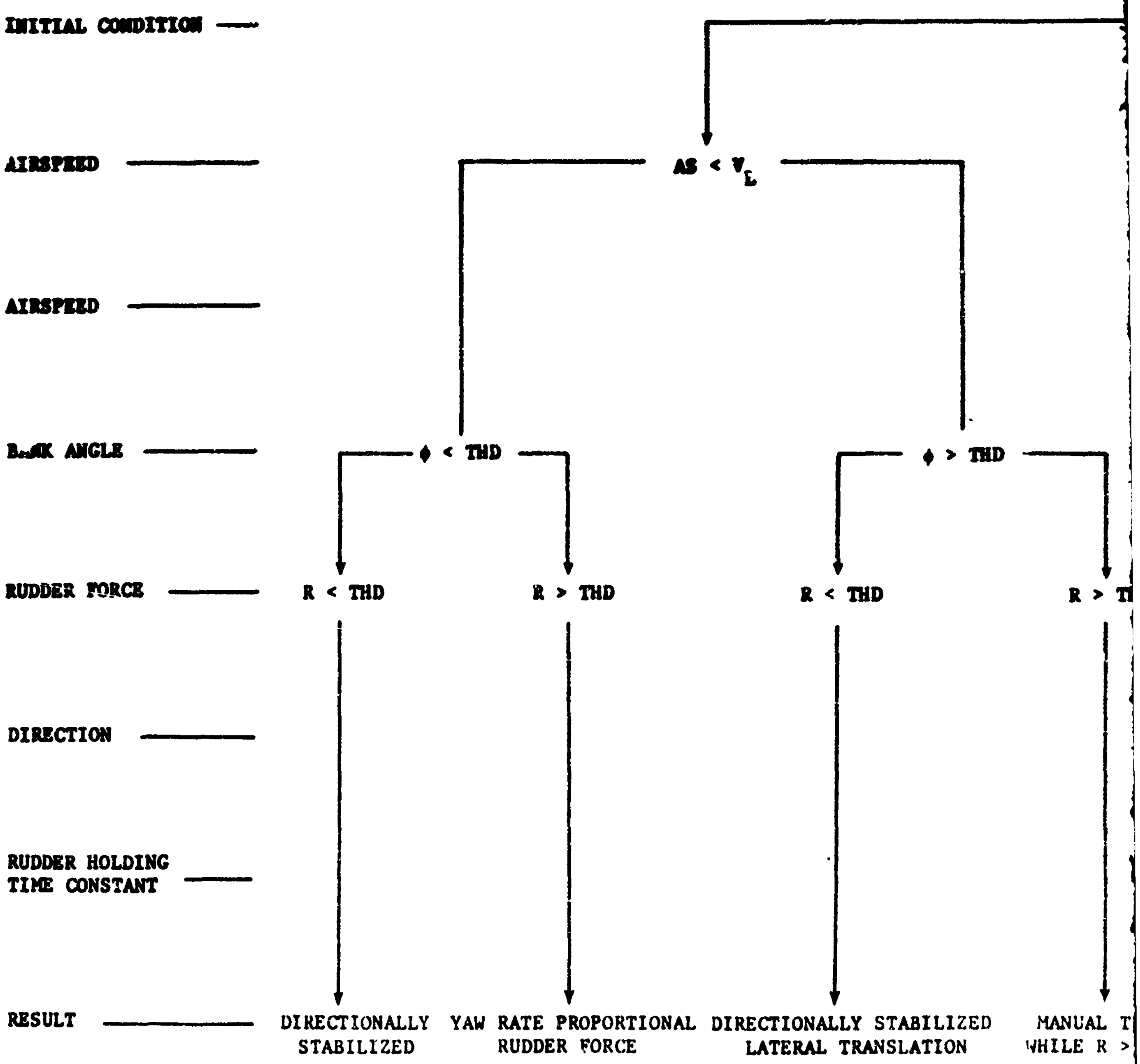
TABLE V

YAW AXIS OPERATIONAL MODE
SUMMARY: SYSTEM DIFFERENCES

OPERATIONAL MODE	SPEED REGIME		
	Hover	High Taxi	Cruise
Automatic Coordinated Turn	Concept - None Differences - None	Concept - When pilot intent is expressed by application of rudder force in direction of bank. Differences - (CH-3C, H-300) 1. CH-3C - when bank angle exceeds bank angle threshold. No rudder pedal forces required to engage auto-coordinated turn. 2. H-300 - when pilot intent is expressed by application of rudder force for three seconds in direction of bank.	Concept - When bank angle exceeds bank angle threshold. Differences - None
Directionally Stabilized Lateral Translation	Concept - When roll attitude deviates from wing level. Differences - None	Concept - When pilot intent is expressed by application of rudder pedal force in direction opposite bank angle. Differences - (Hover Simulator, H-300) 1. Hover Simulator - when bank is entered and no rudder forces are applied. 2. H-300 - when bank is entered and no rudder forces are applied.	Concept - None. (Lateral translation possible by overriding turn coordination command signal.) Differences - (Hover Simulator, H-300) 1. Hover Simulator - lateral translation possible by deactivating turn coordination computer. 2. H-300 - directionally stabilized lateral translation possible only if in this mode prior to entering cruise regime.
Directionally Stabilized Mode	Concept - when roll attitude is wing level. Yaw rate proportional to rudder pedal force. Differences - None	Concept - When bank angle is less than bank angle threshold. Yaw rate proportional to rudder pedal force. Differences - None	Concept - When bank angle is less than bank angle threshold. Yaw rate proportional to rudder pedal force. Differences - None

devices without infringing upon the command prerogatives of the pilot. In each system the pilot is able to constantly retain absolute command over the control functions, thus permitting him to impose his will upon the systems without compromising the advantages of the automatics. The major differences between the systems discussed here have been the result of the unique requirements of each test vehicle. These developments serve to demonstrate that not only do the control concepts encompassed within the turn coordination systems retain the advantages of the basic Pilot Manager concept, but that they are sufficiently flexible in their implementation to allow tailoring to the unique requirements of a variety of VTOL vehicles. The flexibility presented in the control concepts is desirable if broad application is to be achieved.

APPENDIX
LOGIC FLOW DIAGRAMS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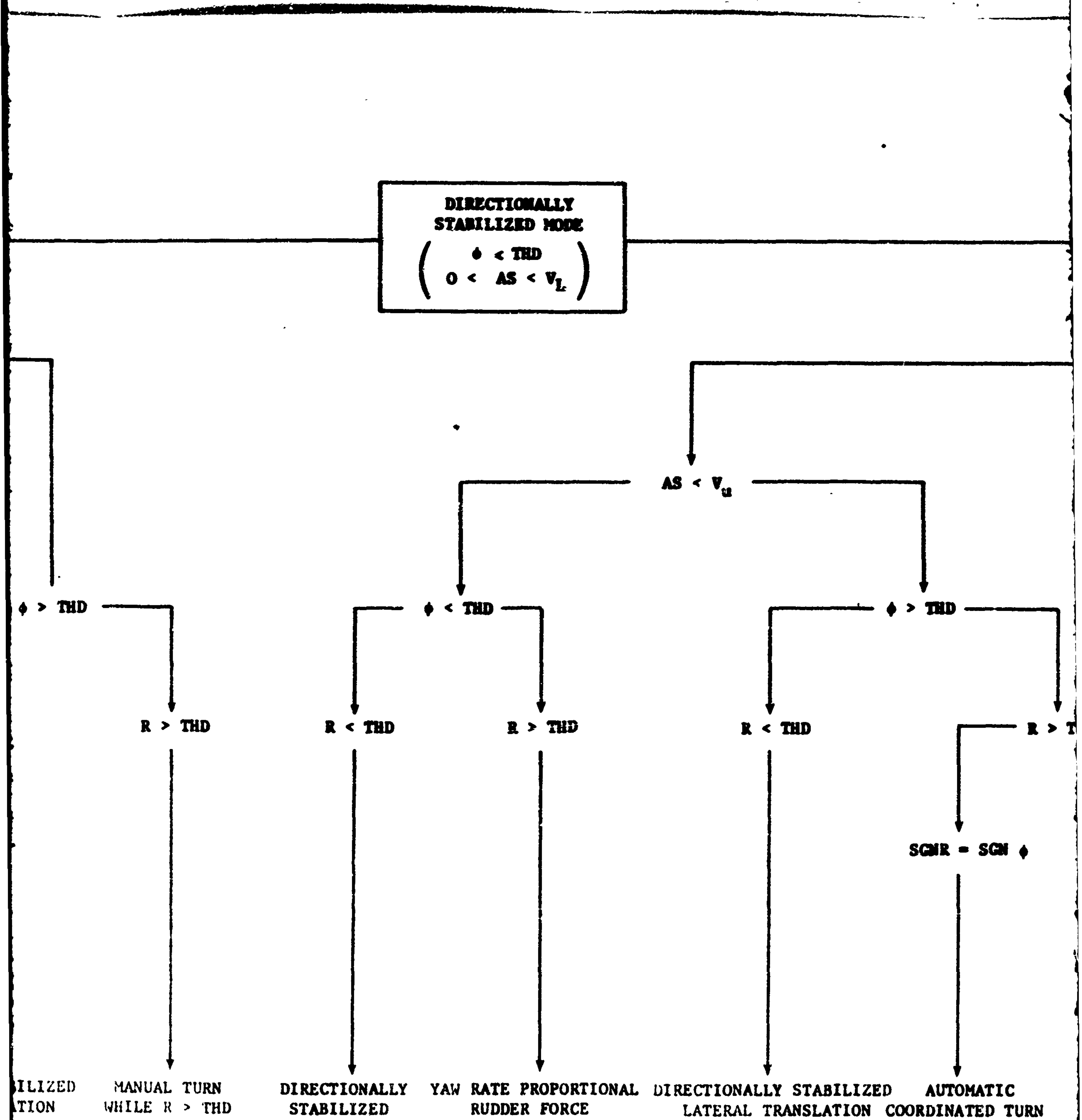
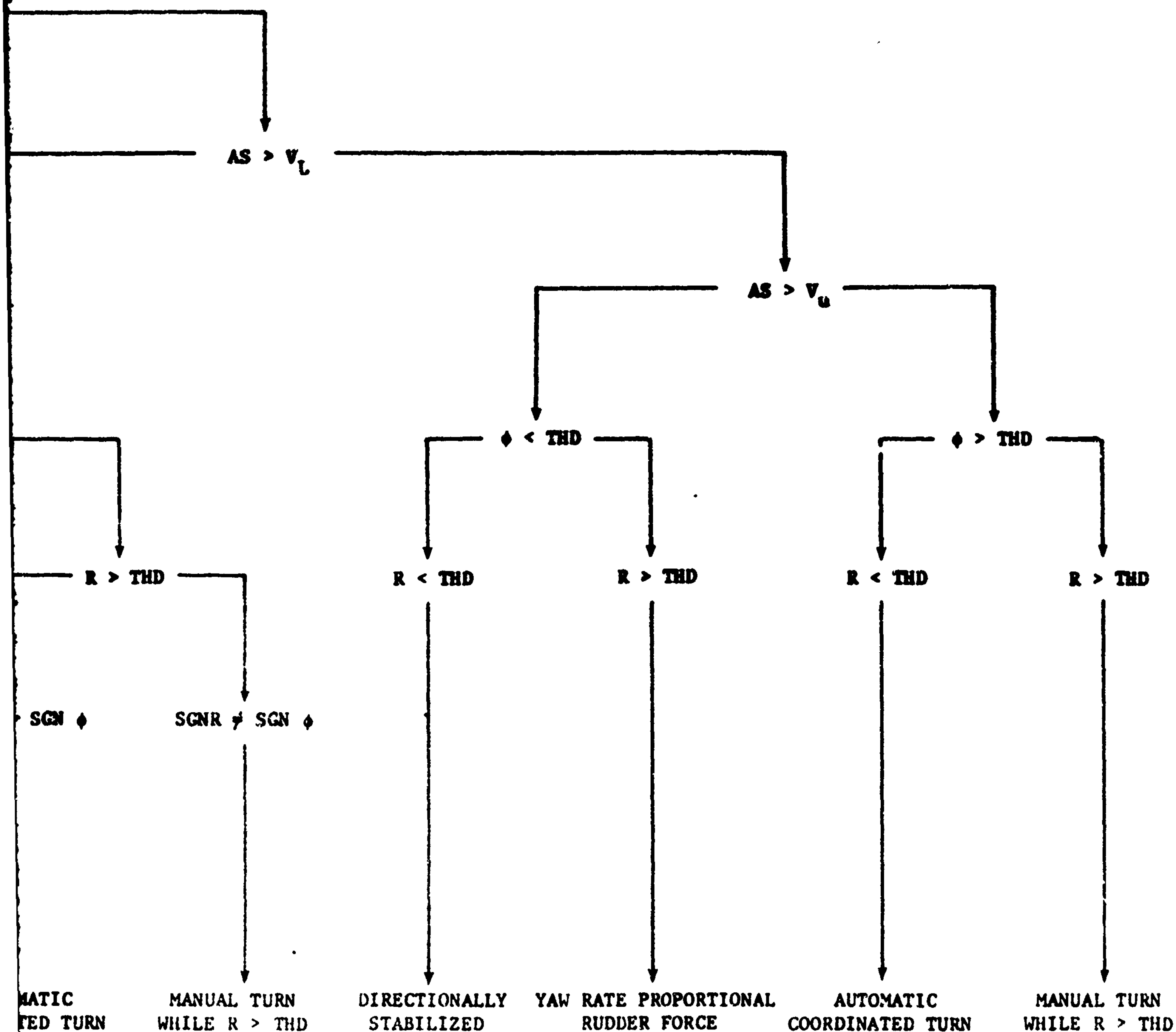


Figure 2. Hover Simulator, Directionally Stabilized Mode



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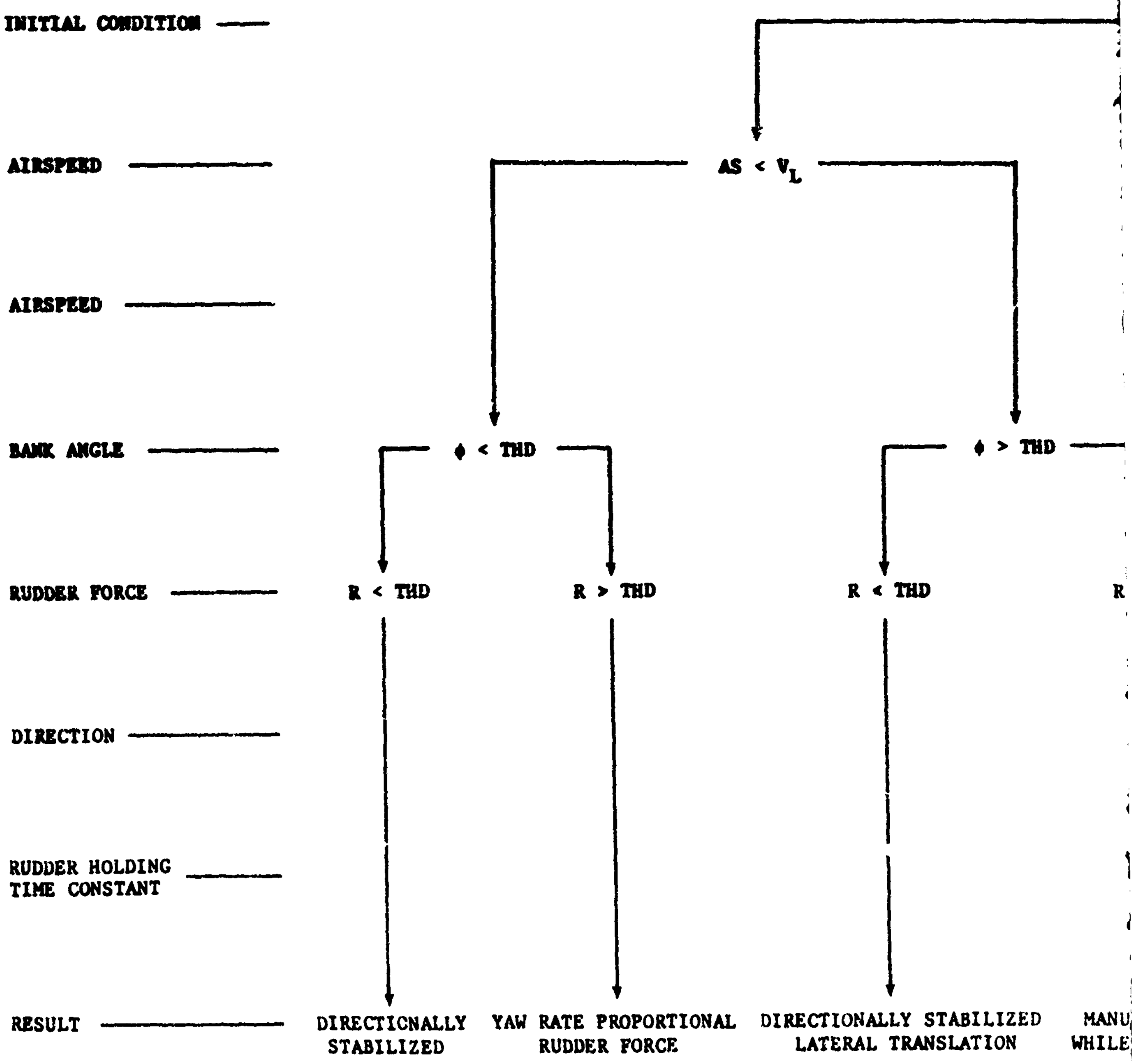
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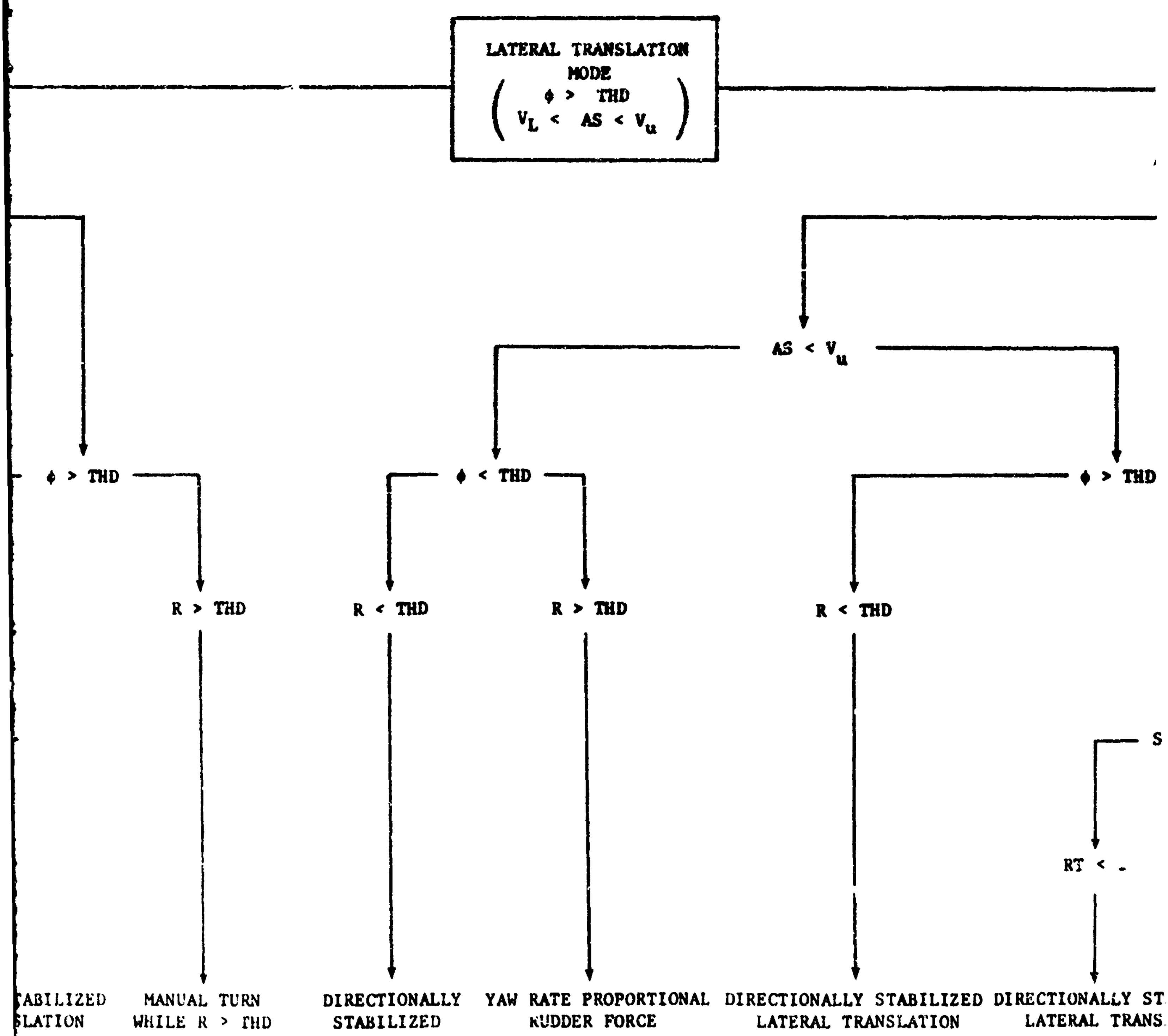
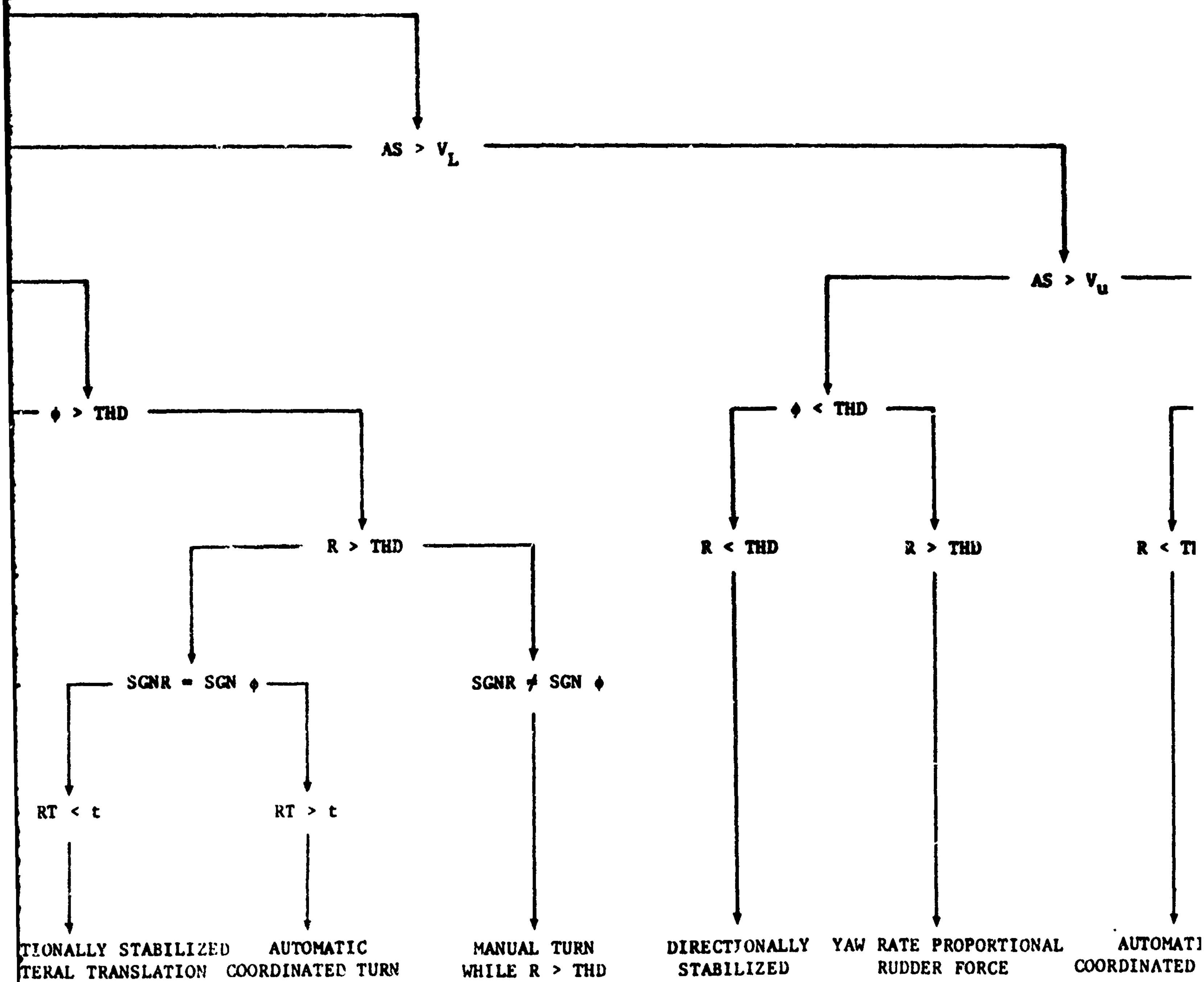


Figure 3. Hover Simulator, Lateral Translation Mode

B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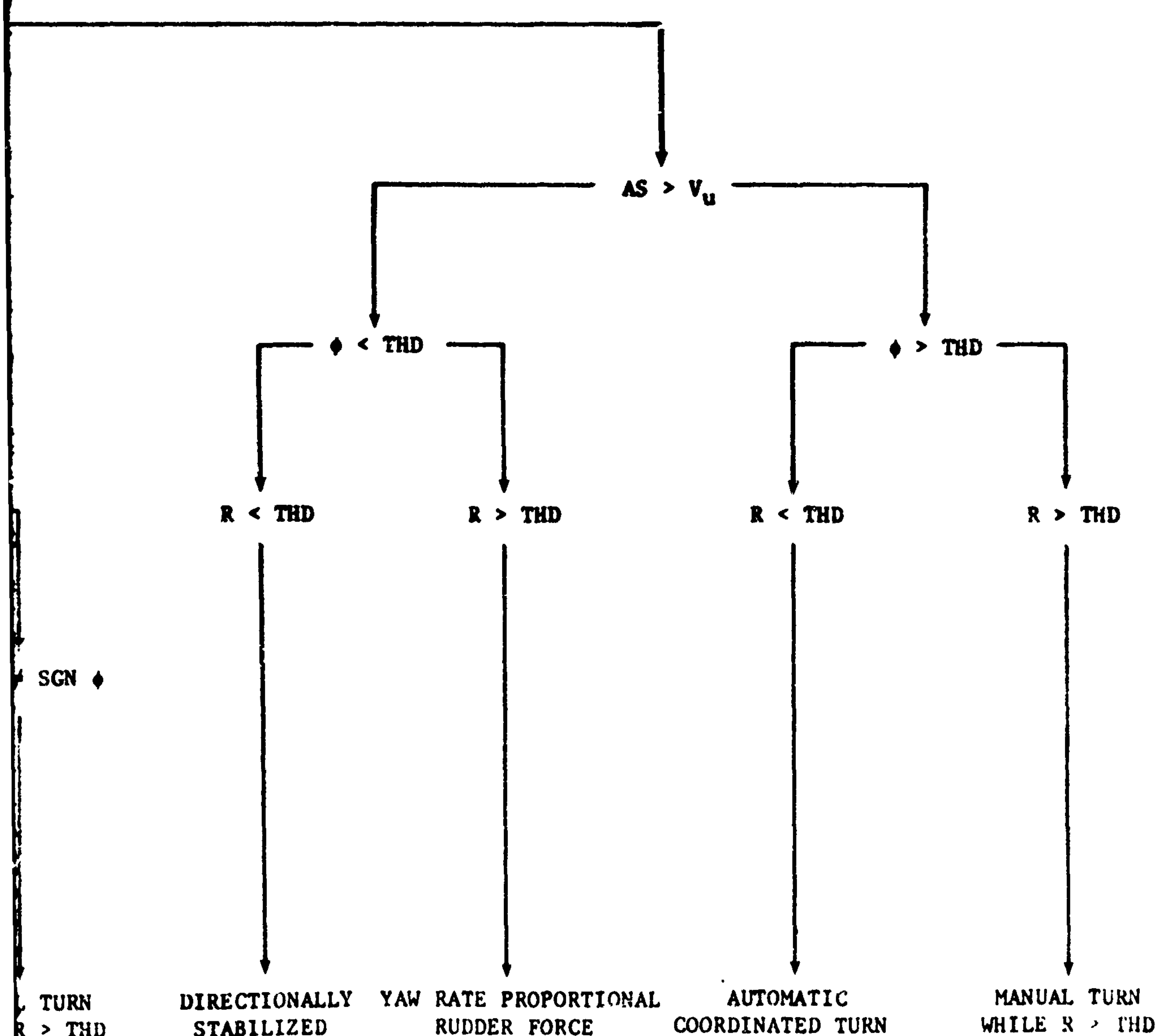

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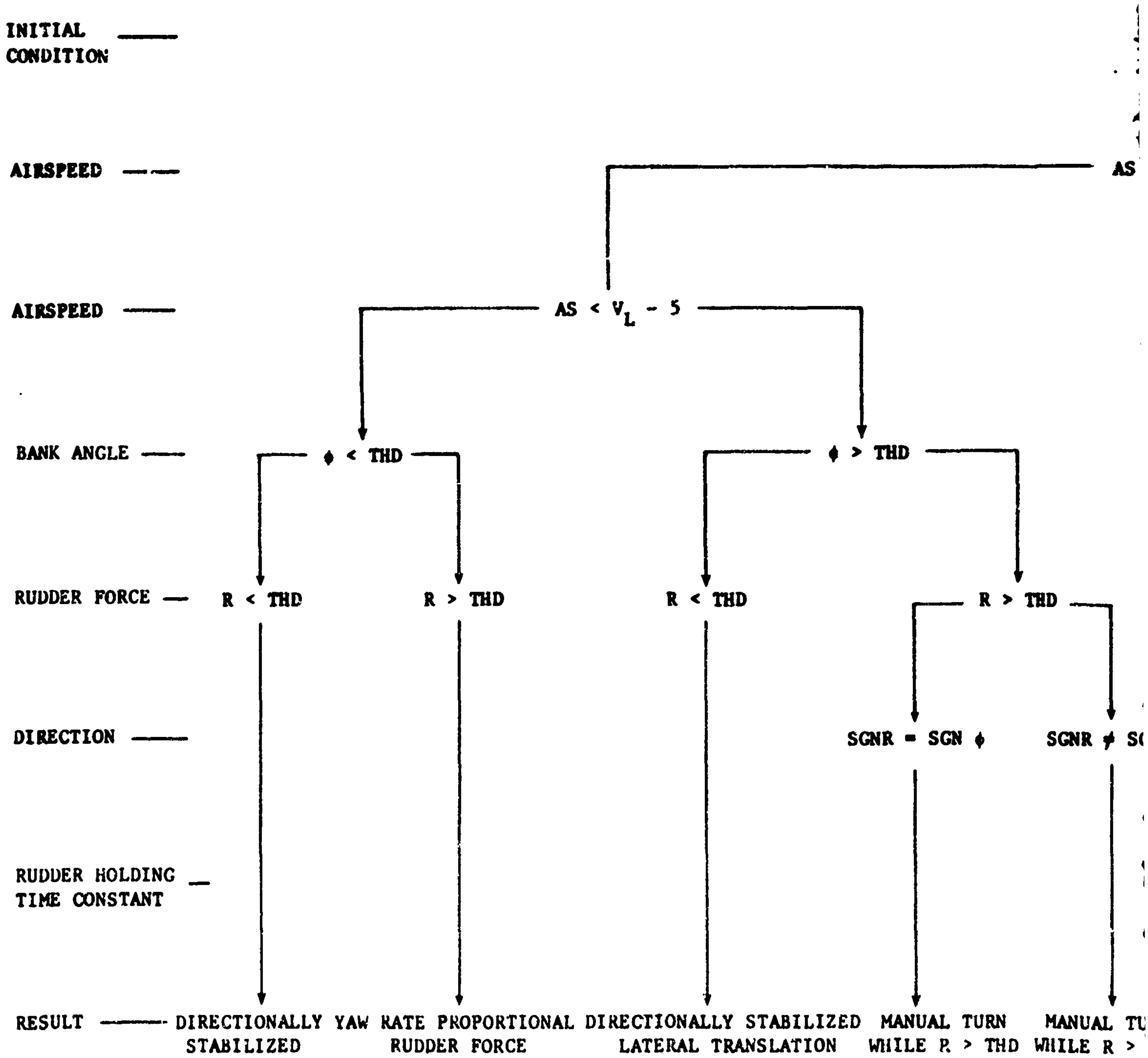

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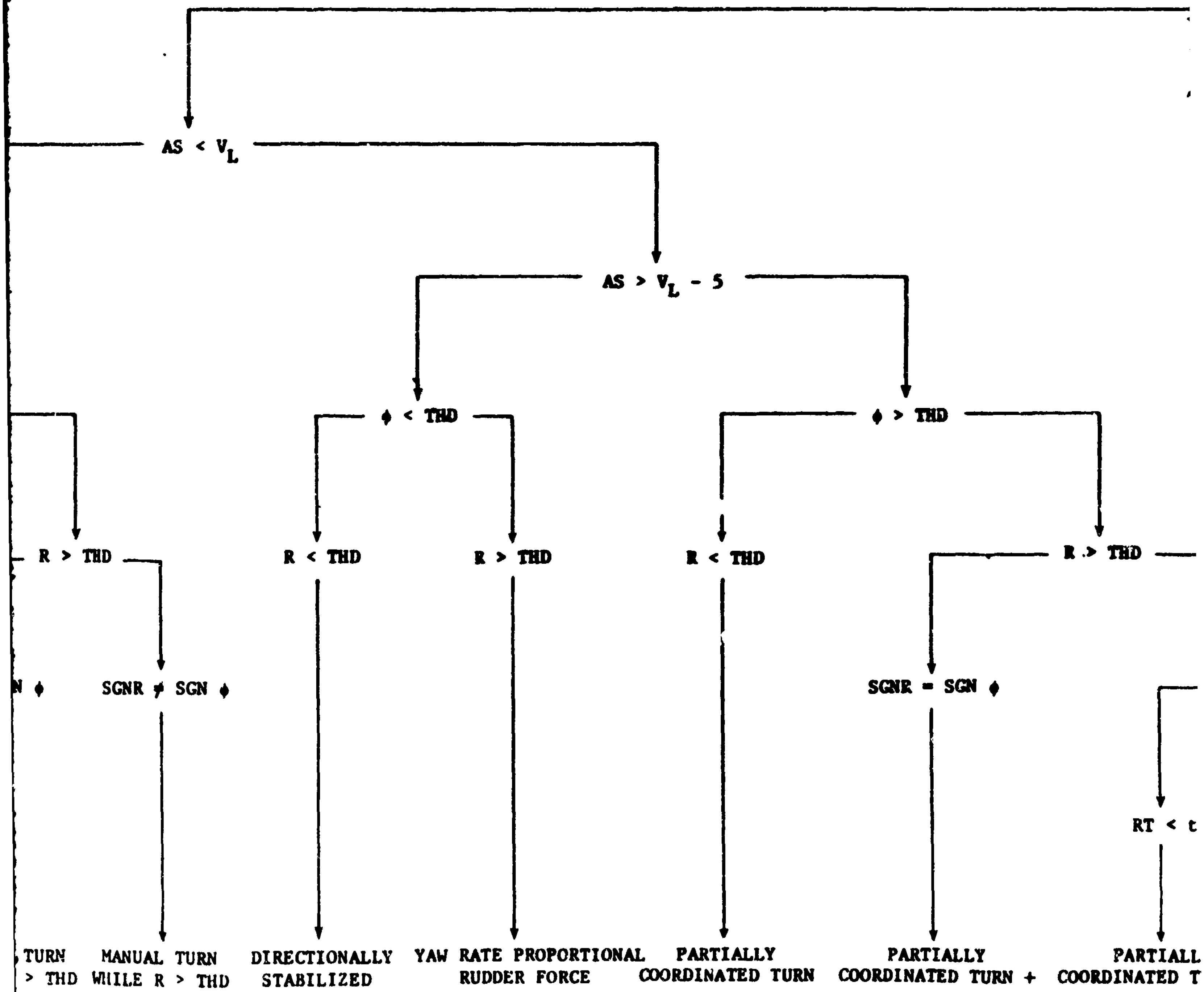

Figure 4. Hover Simul

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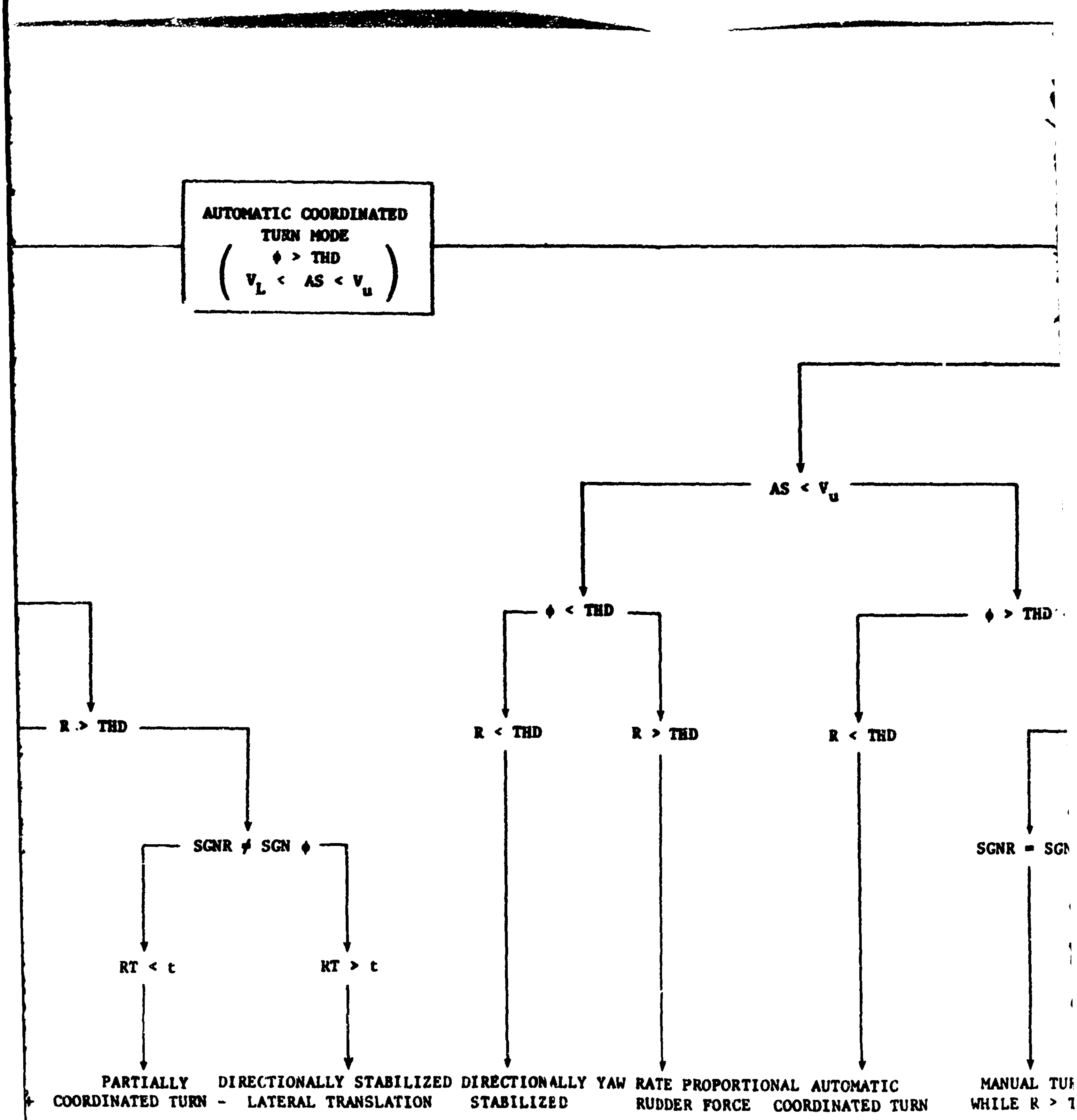
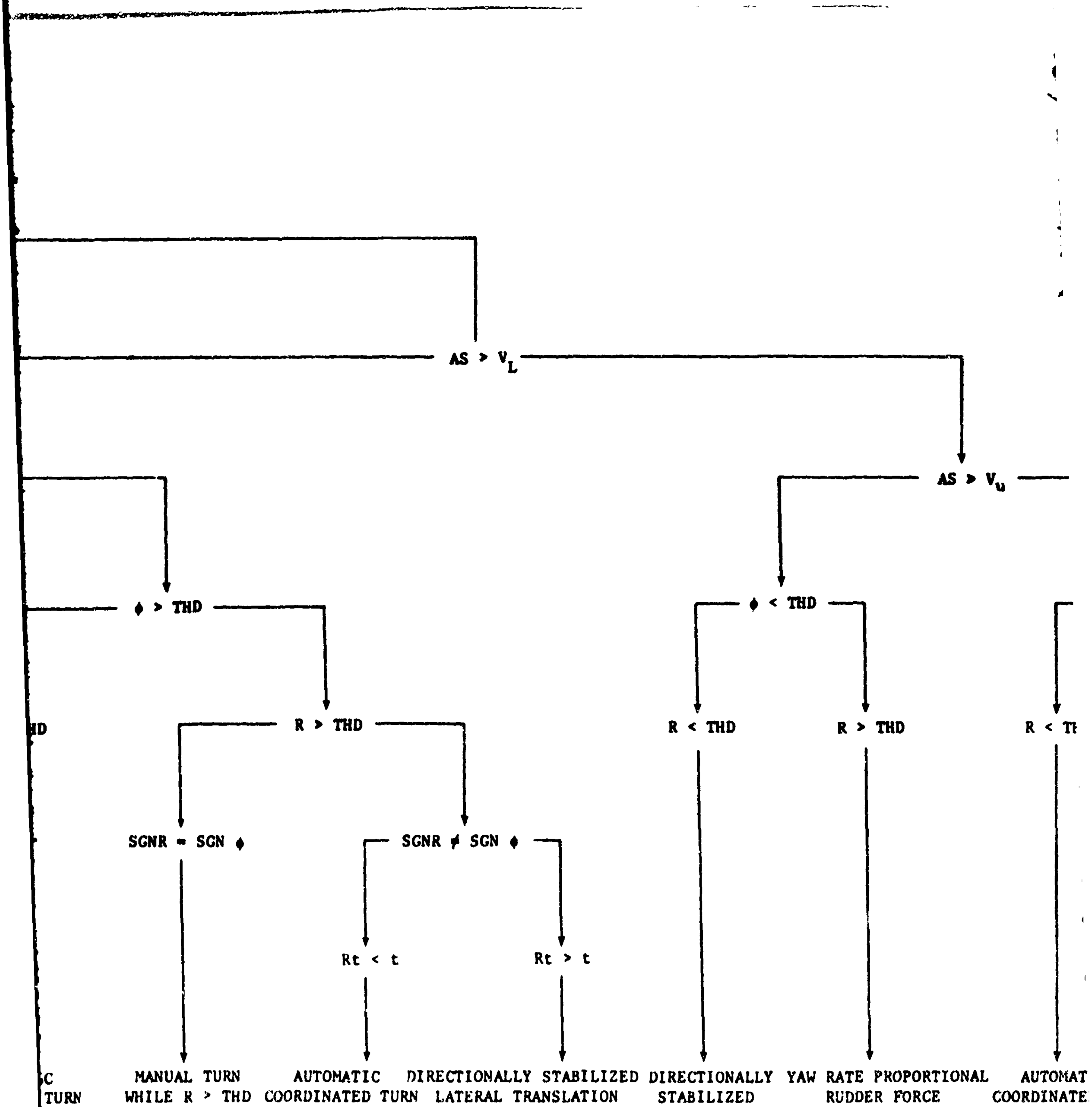


e 4. Hover Simulator, Automatic Coordinated Turn Mode



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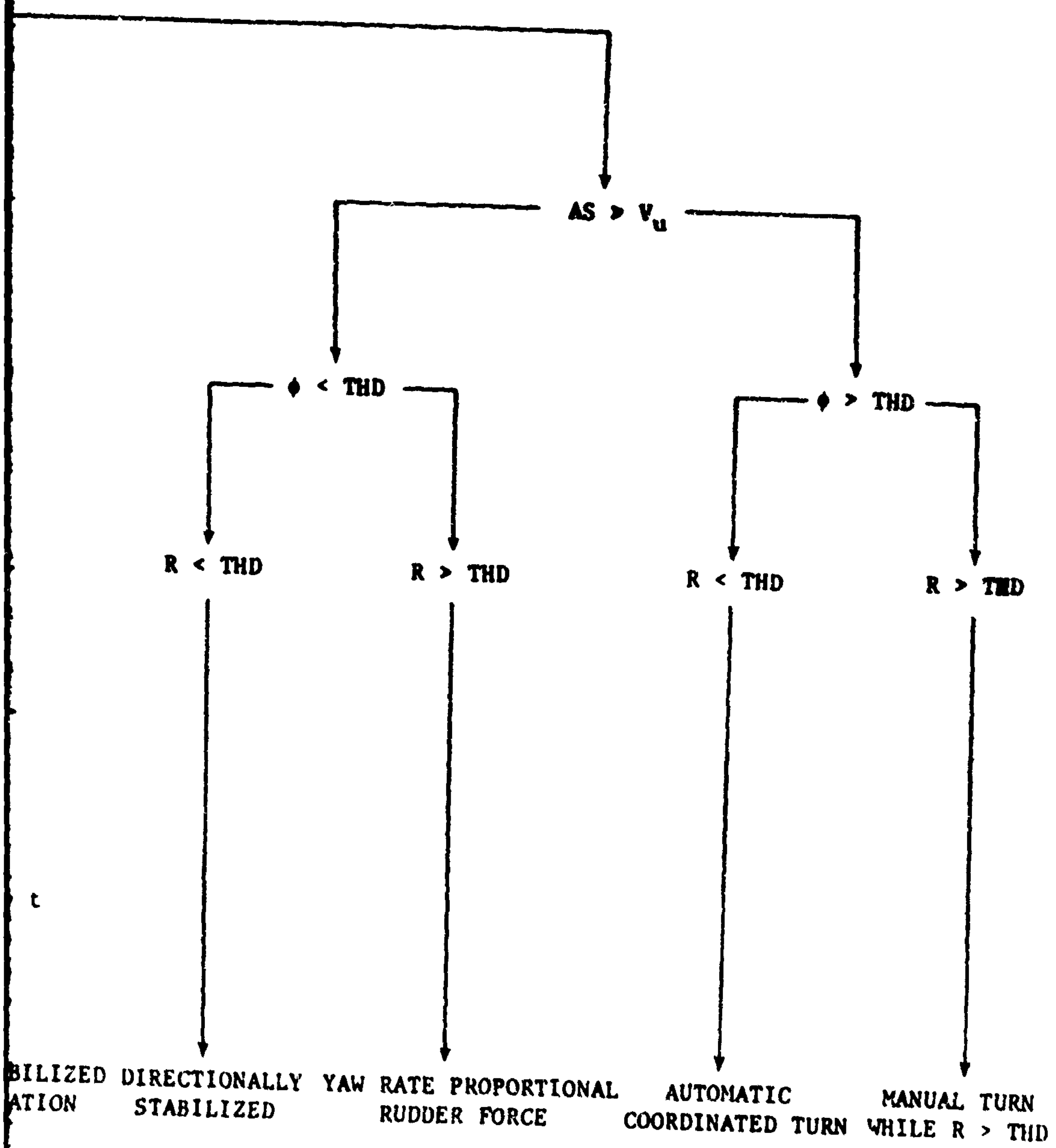
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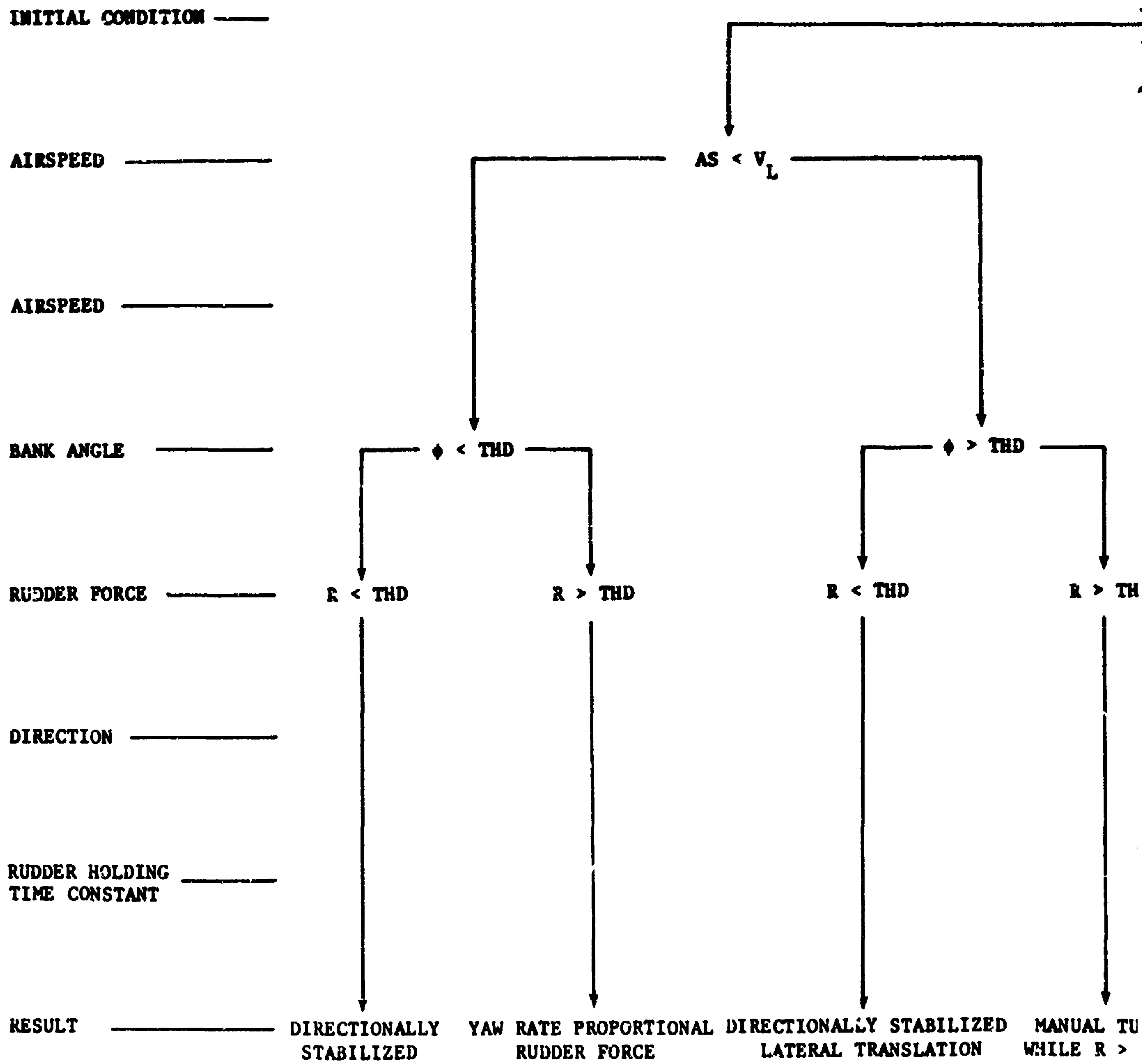
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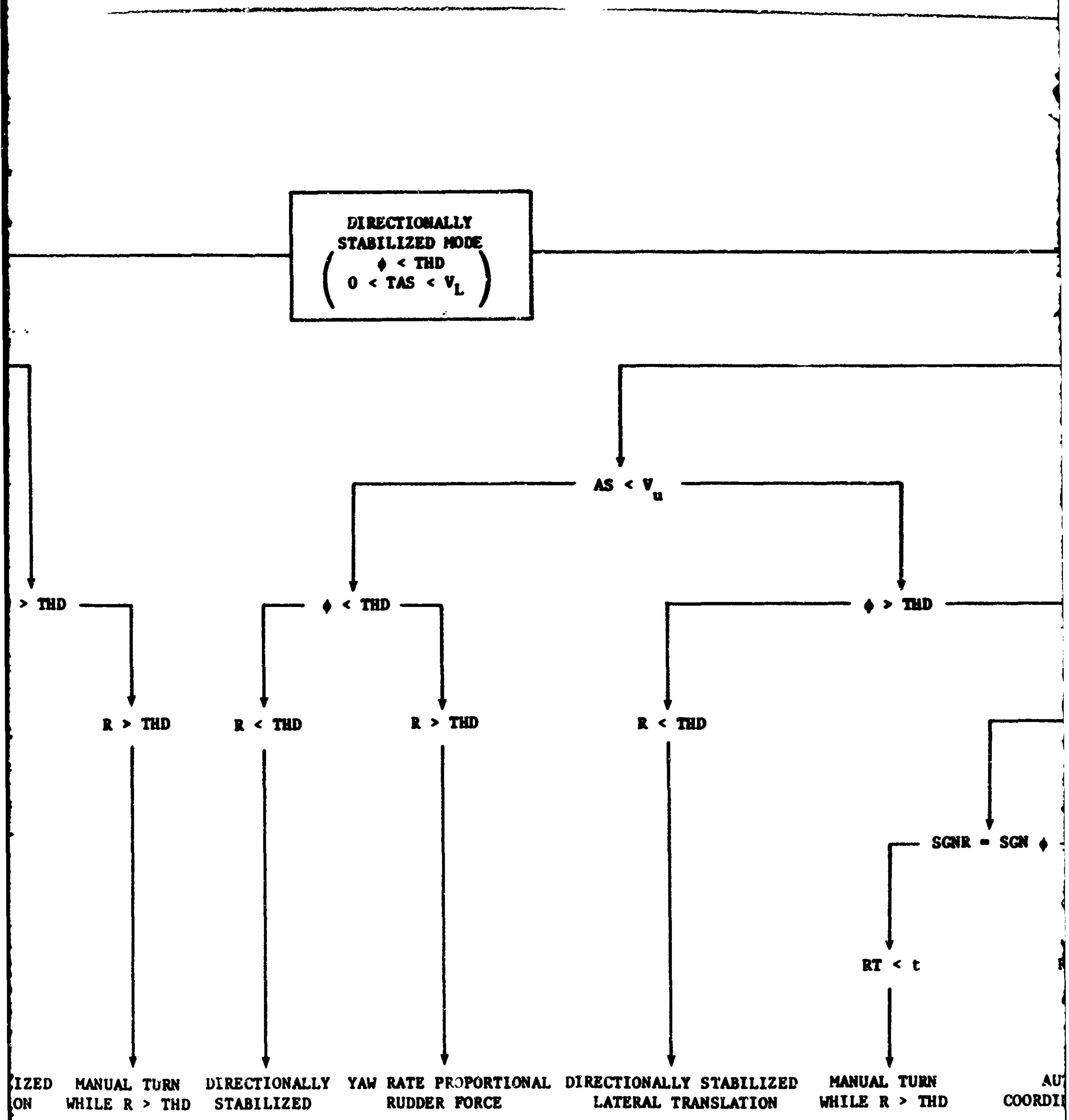
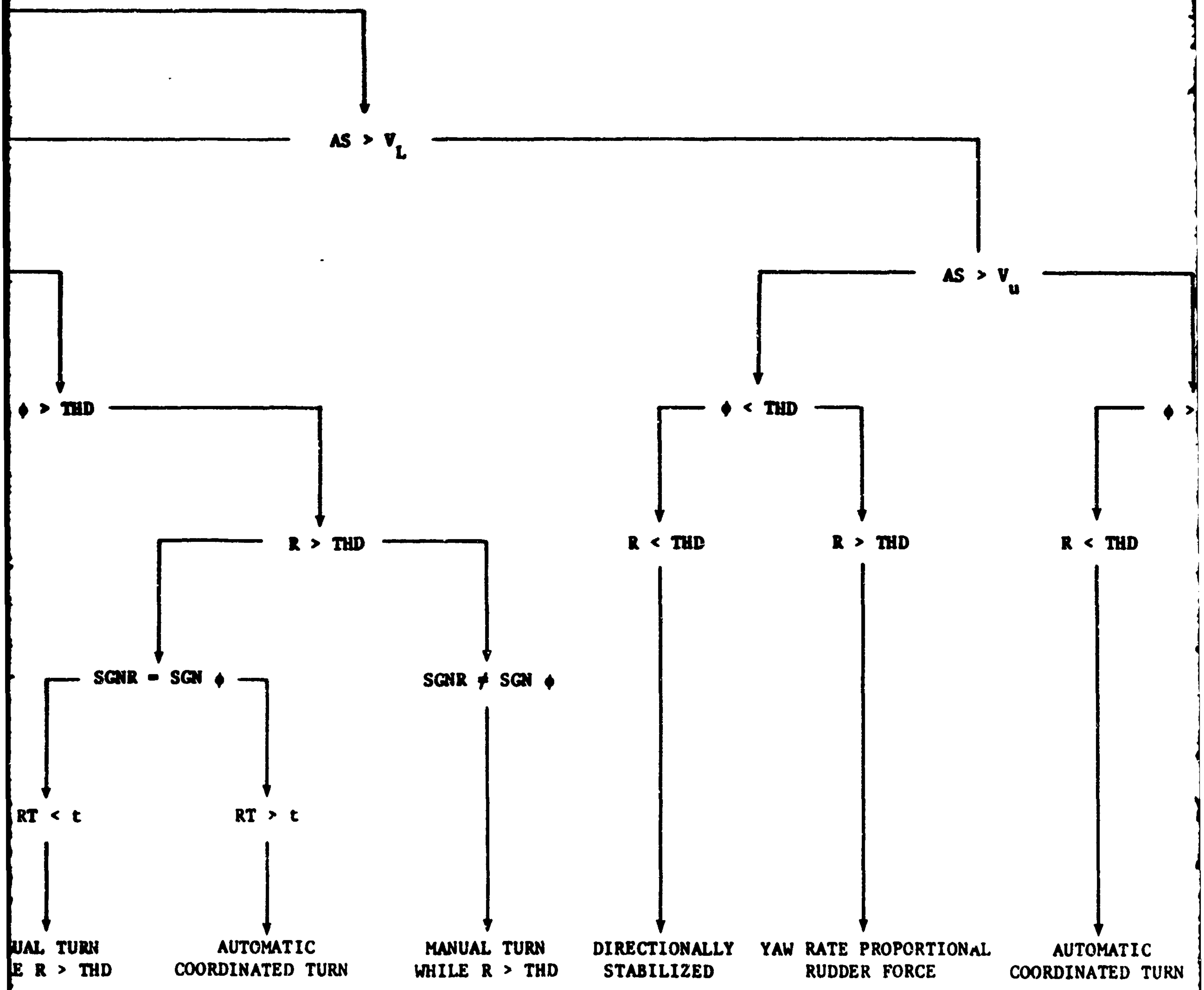


Figure 5. H-300, Directionally Stabilized Mode



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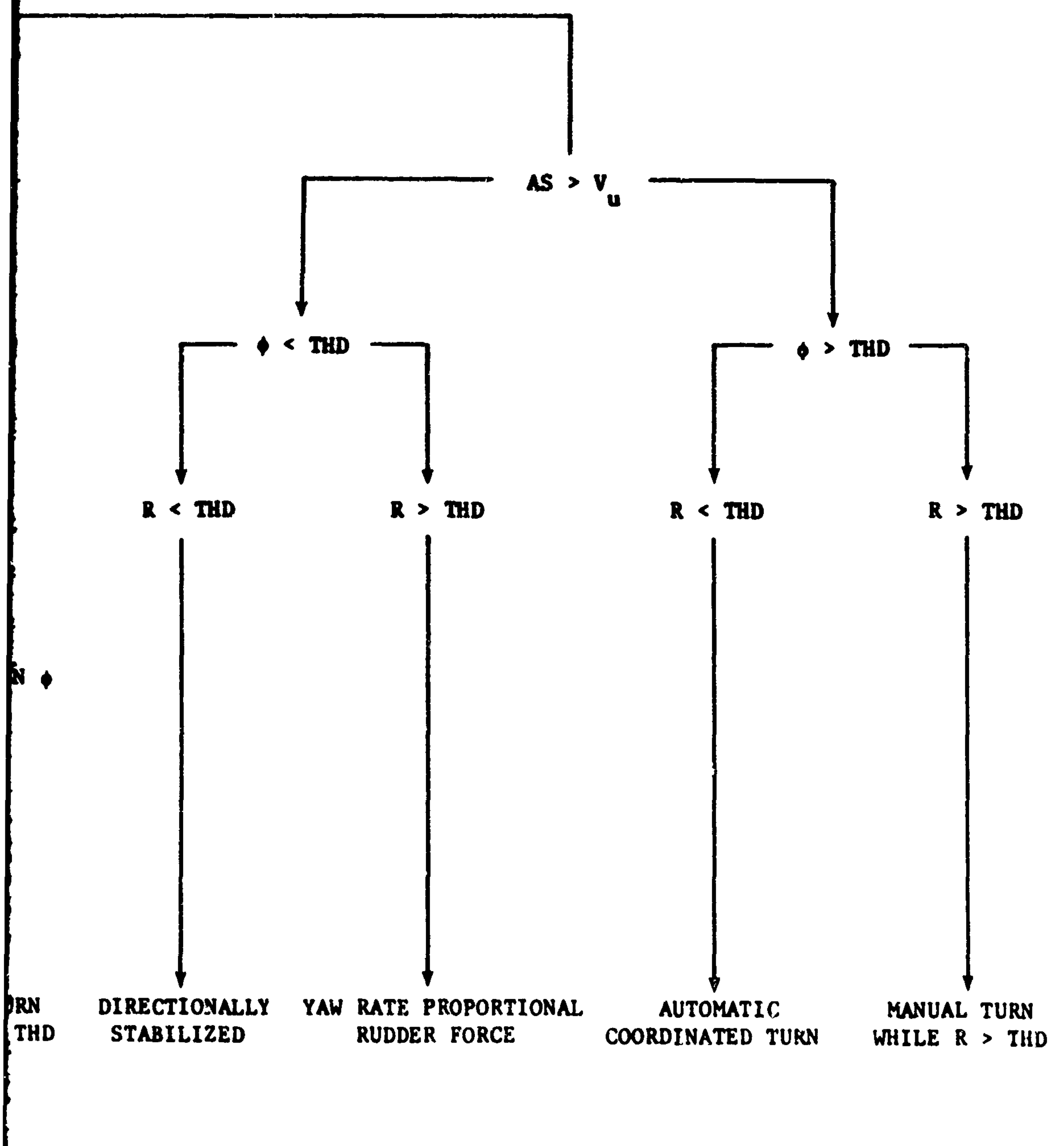
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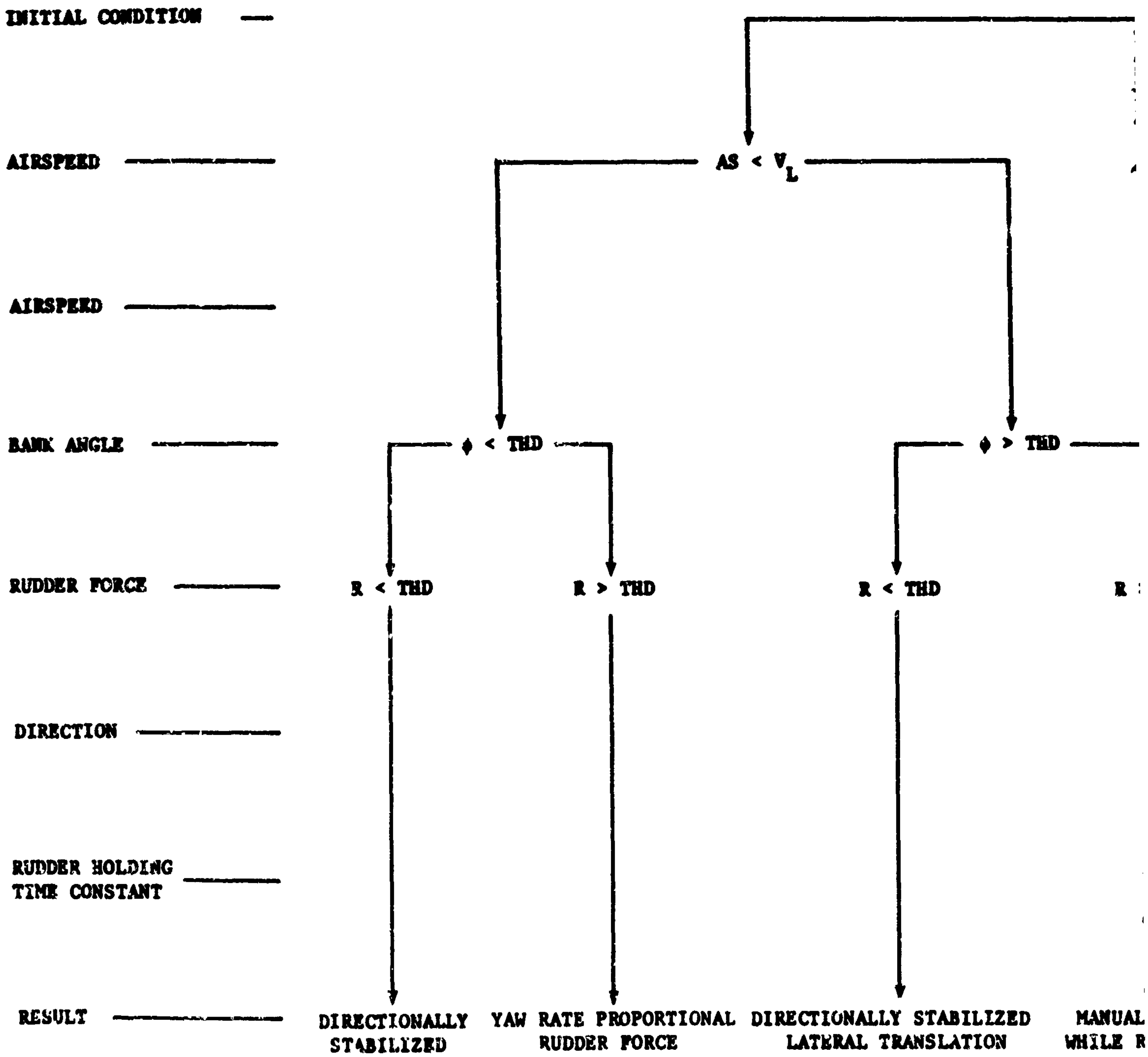
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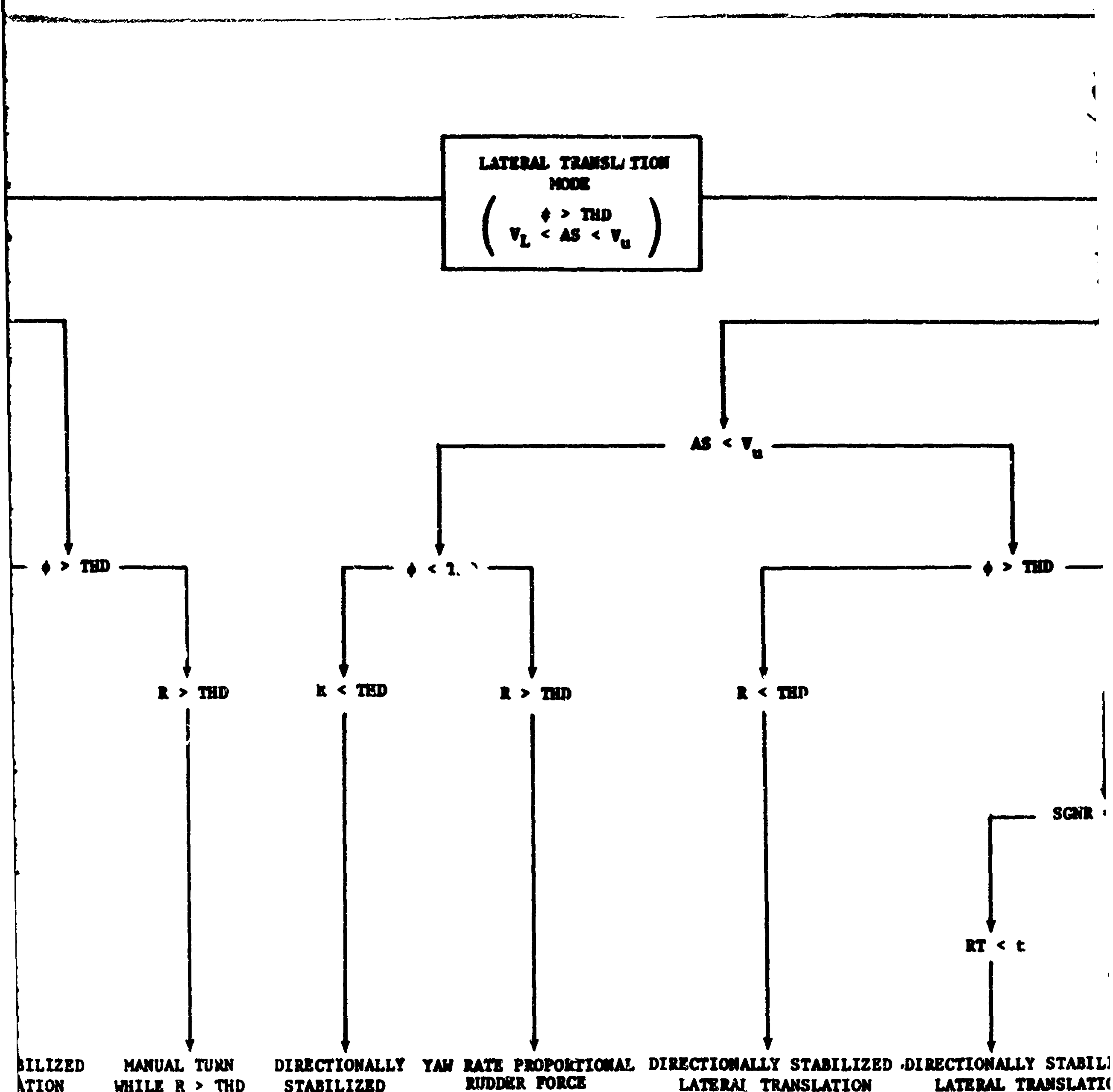

Figure 6. H-300, Lateral Translation Mode

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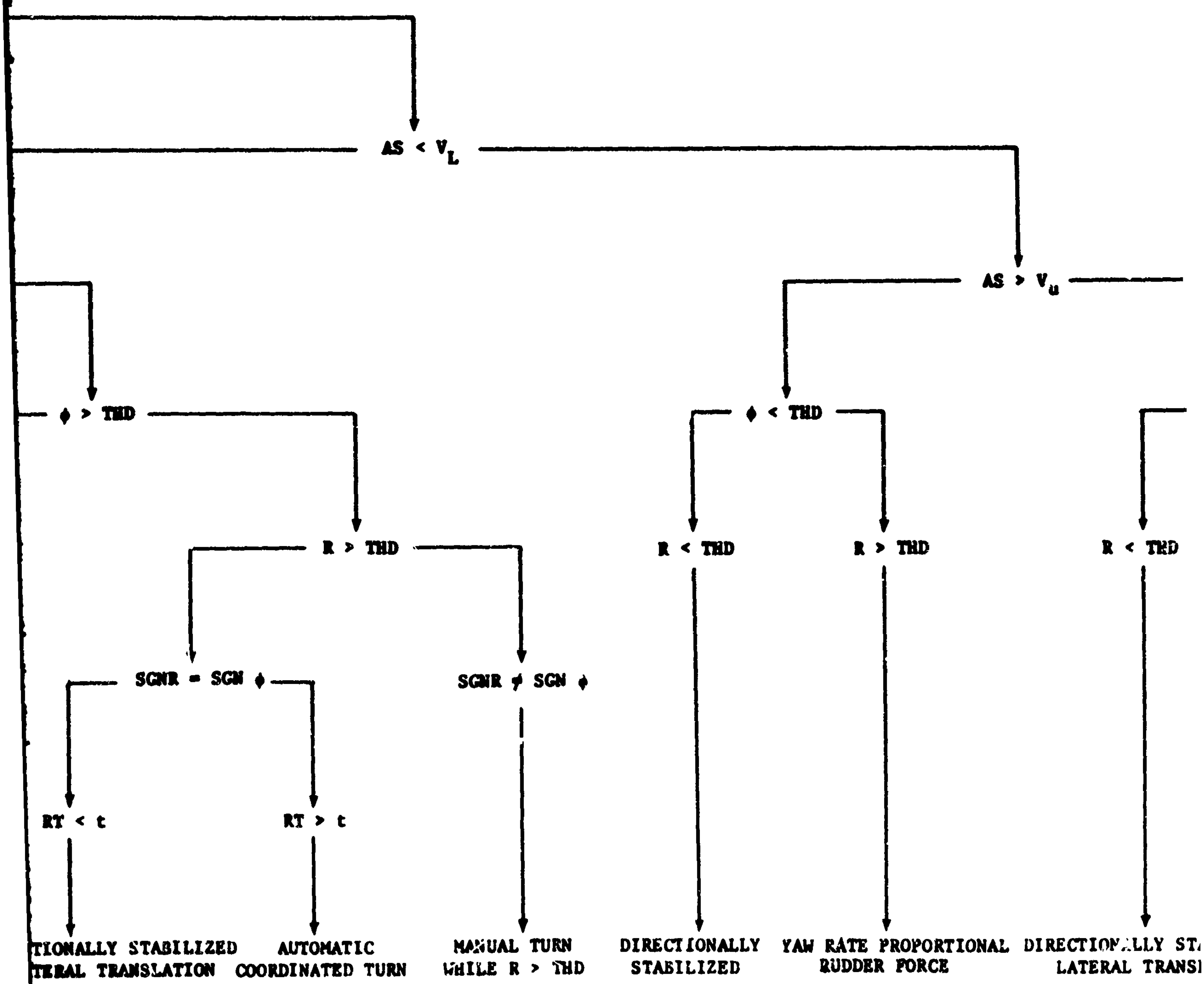

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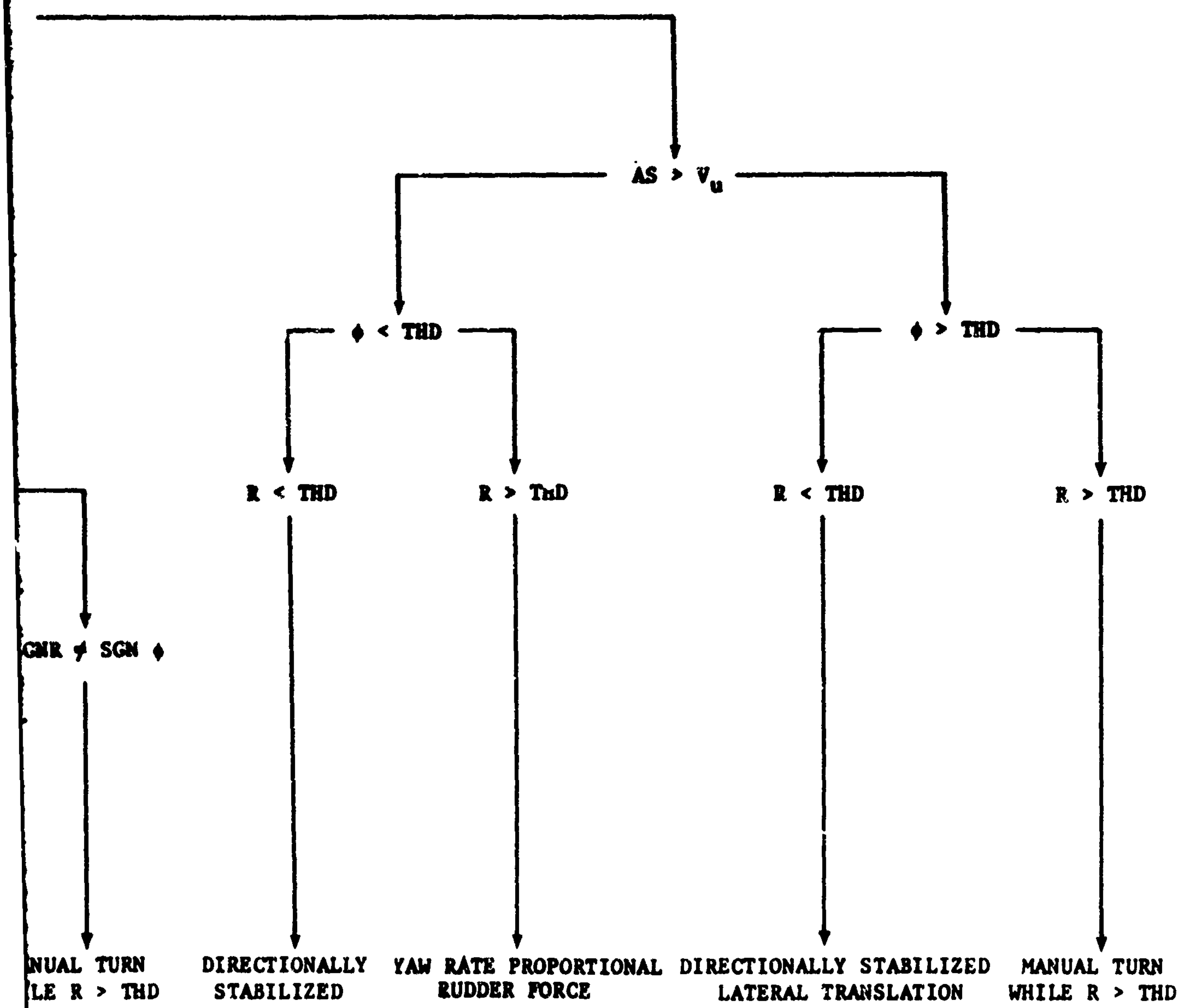
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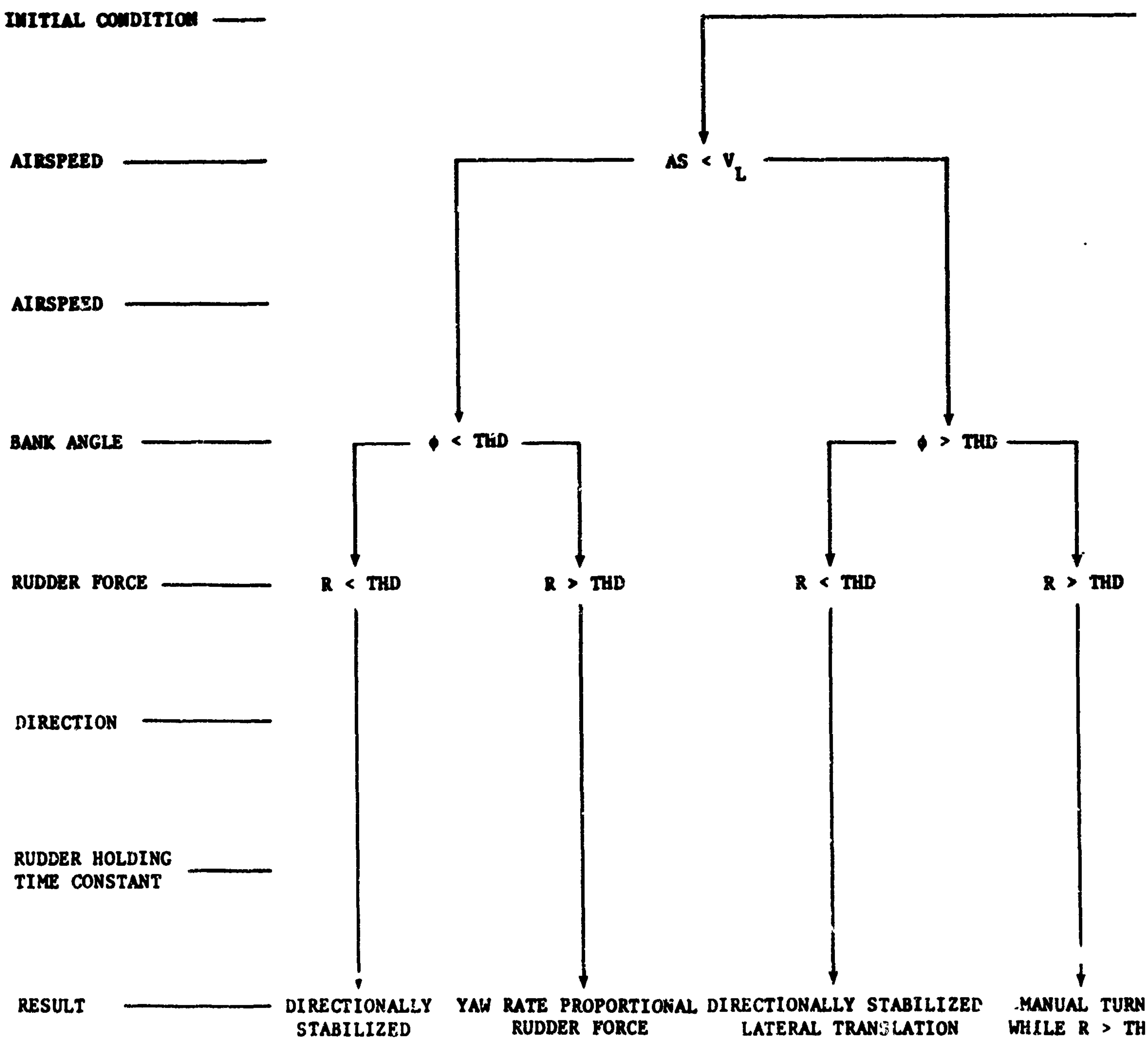
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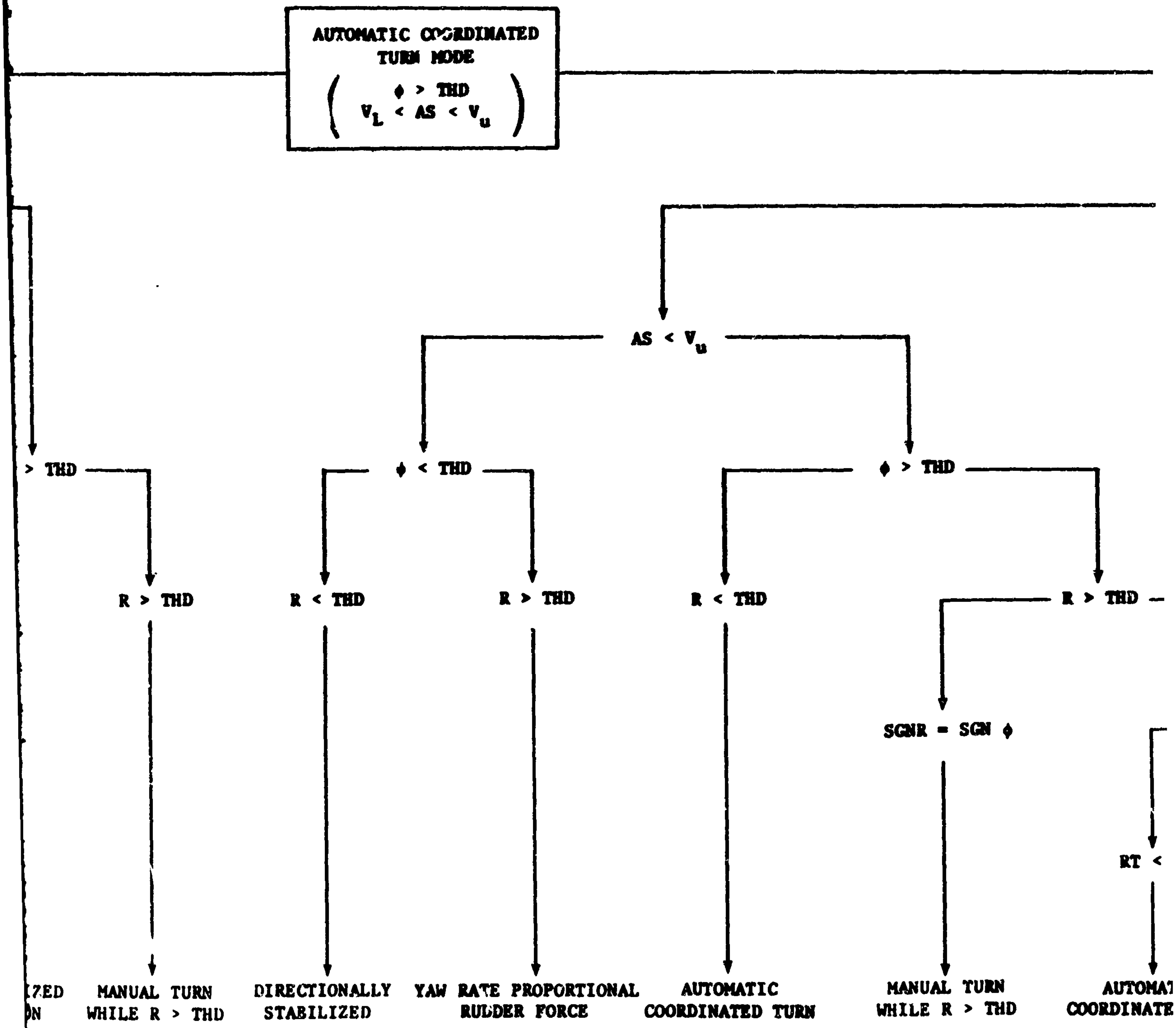
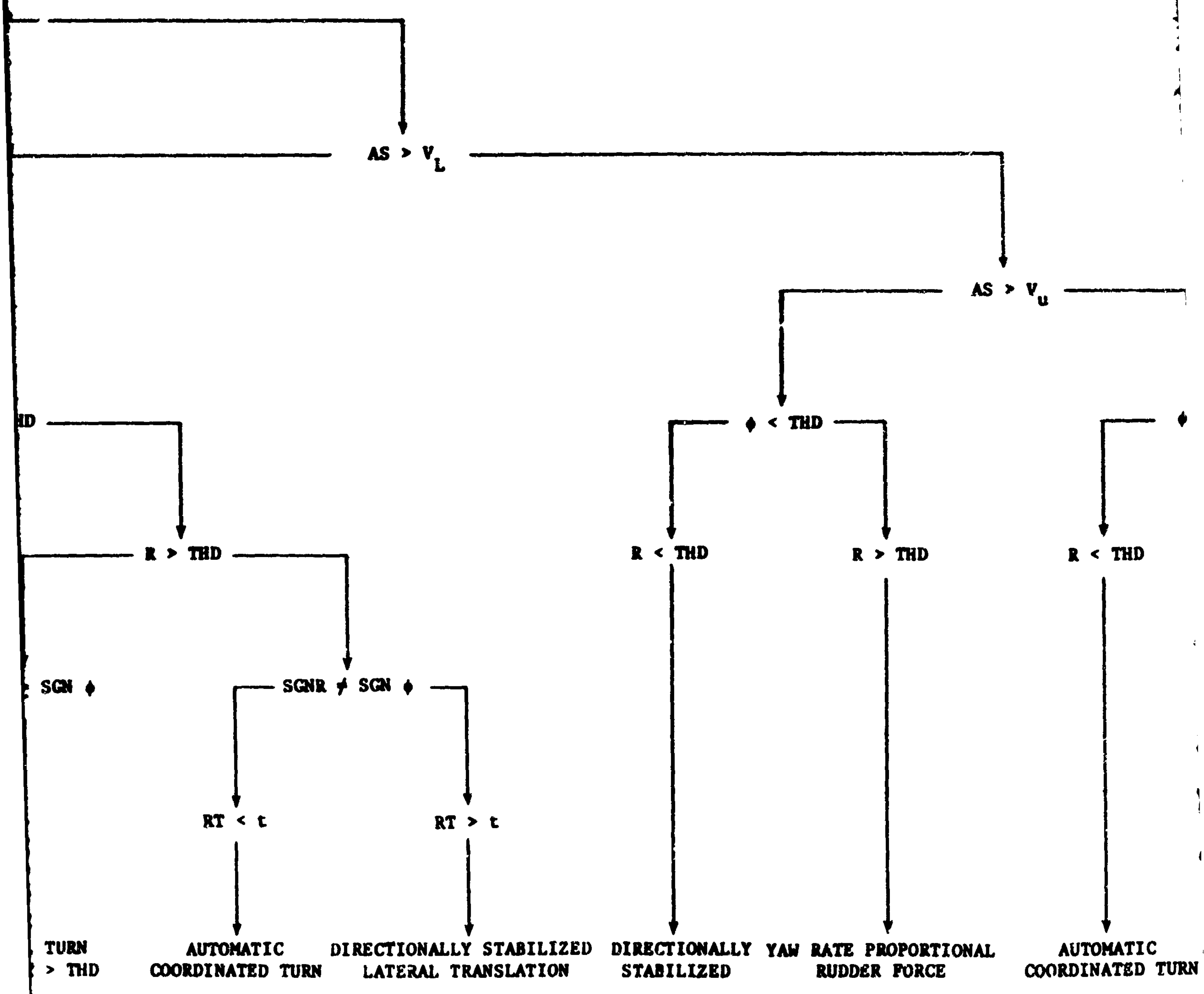


Figure 7. H-300, Automatic Coordinated Turn Mode



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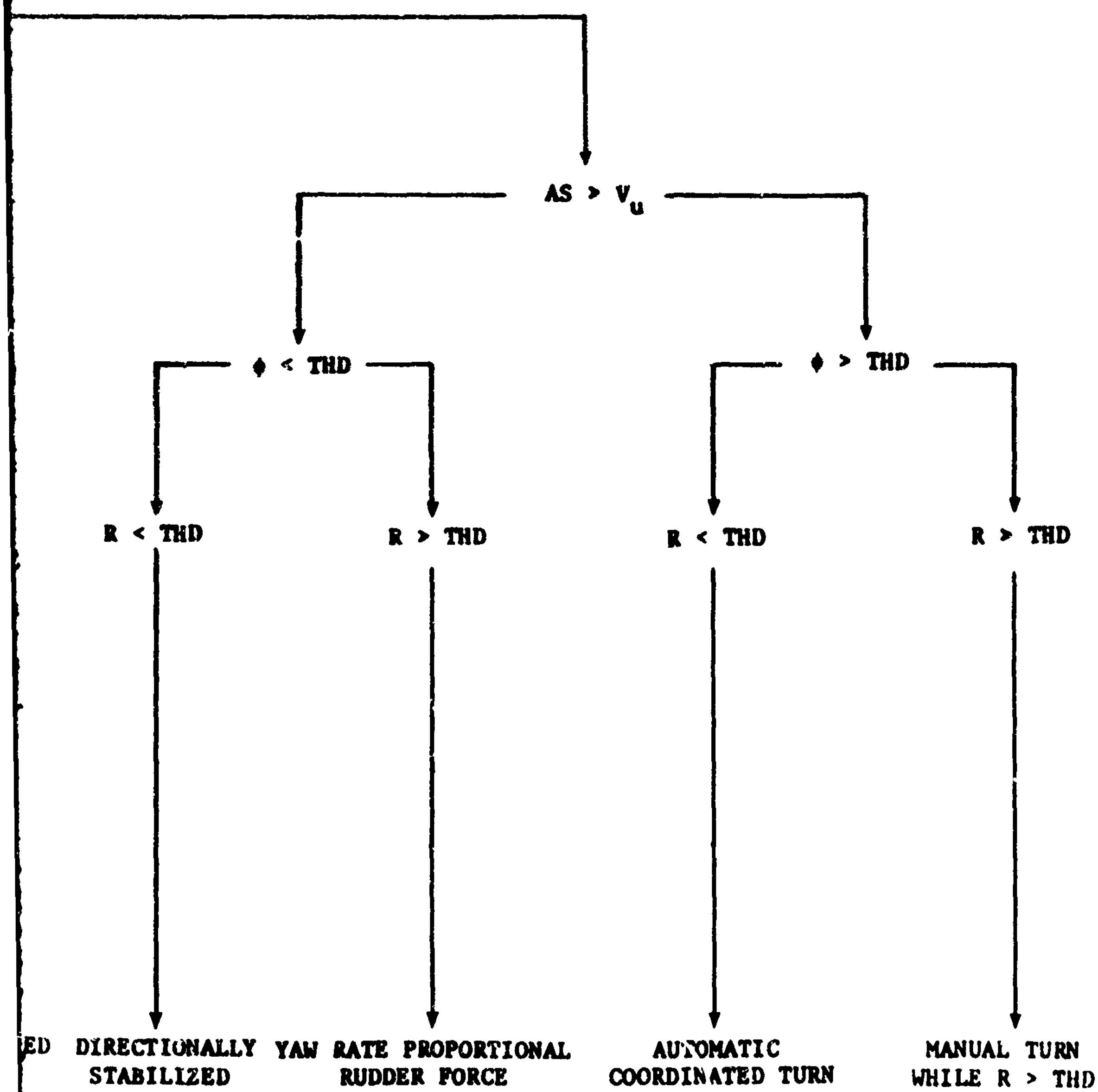
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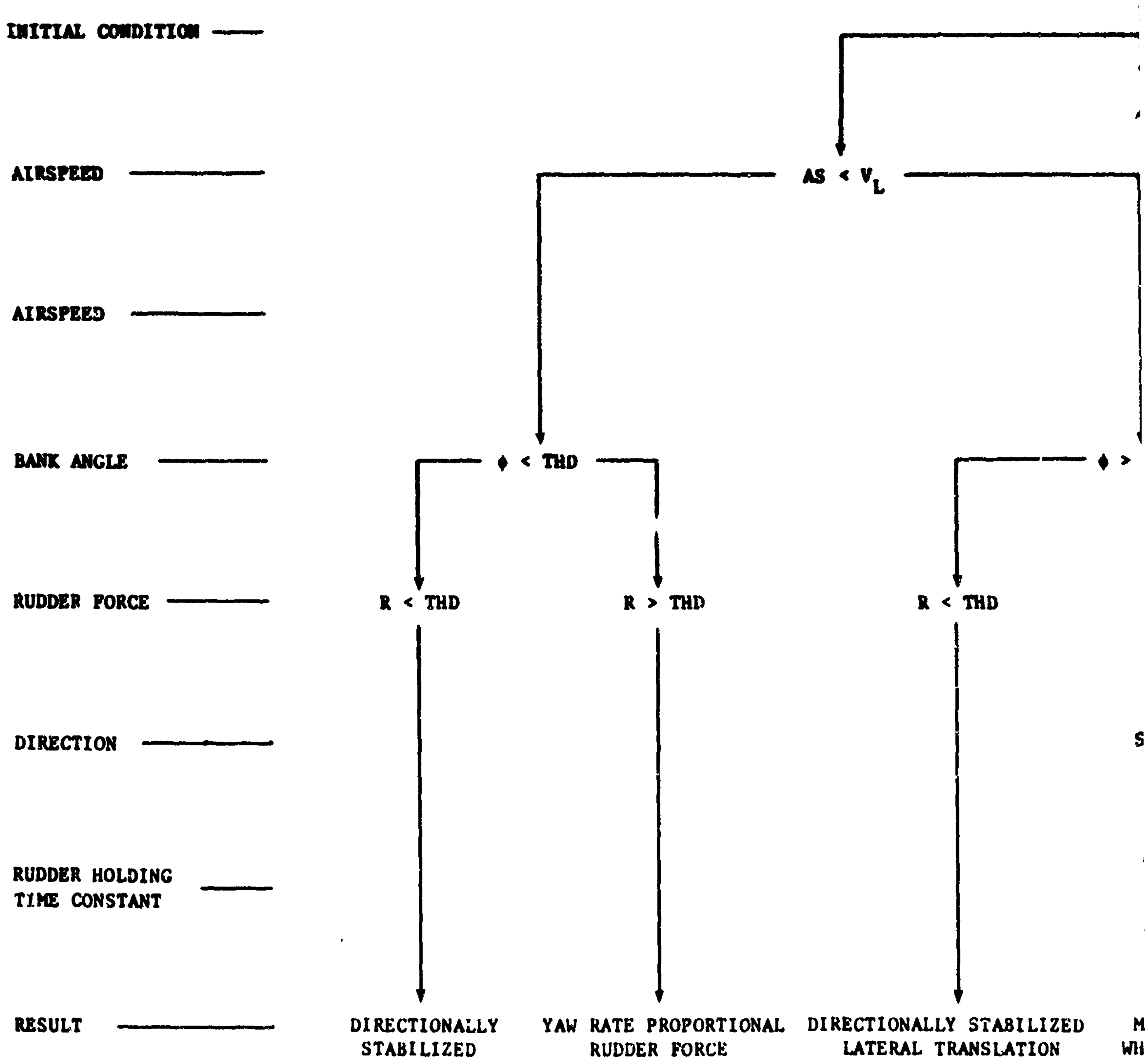
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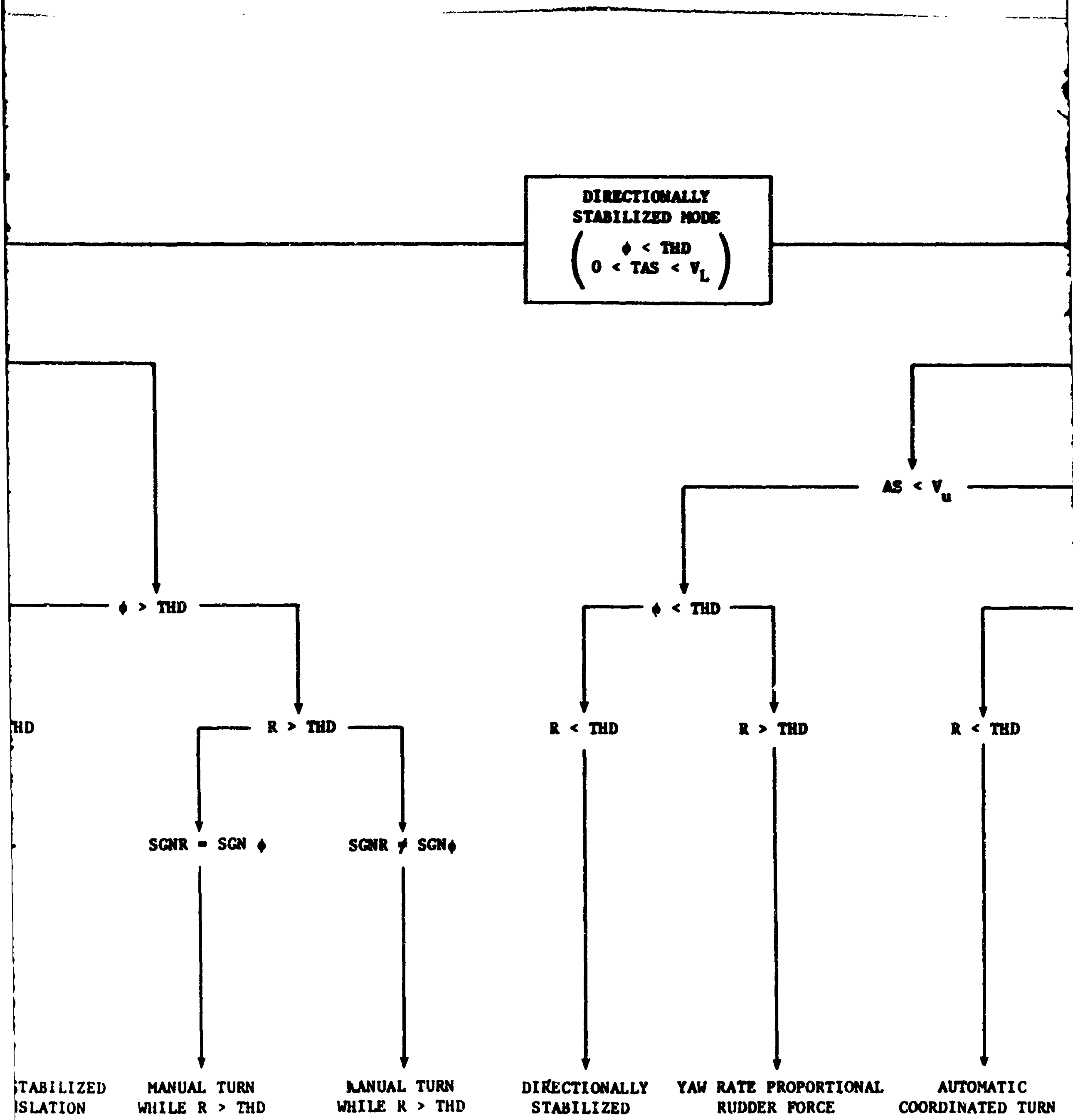

Figure 8. CH-3C, Directionally Stabilized Mode

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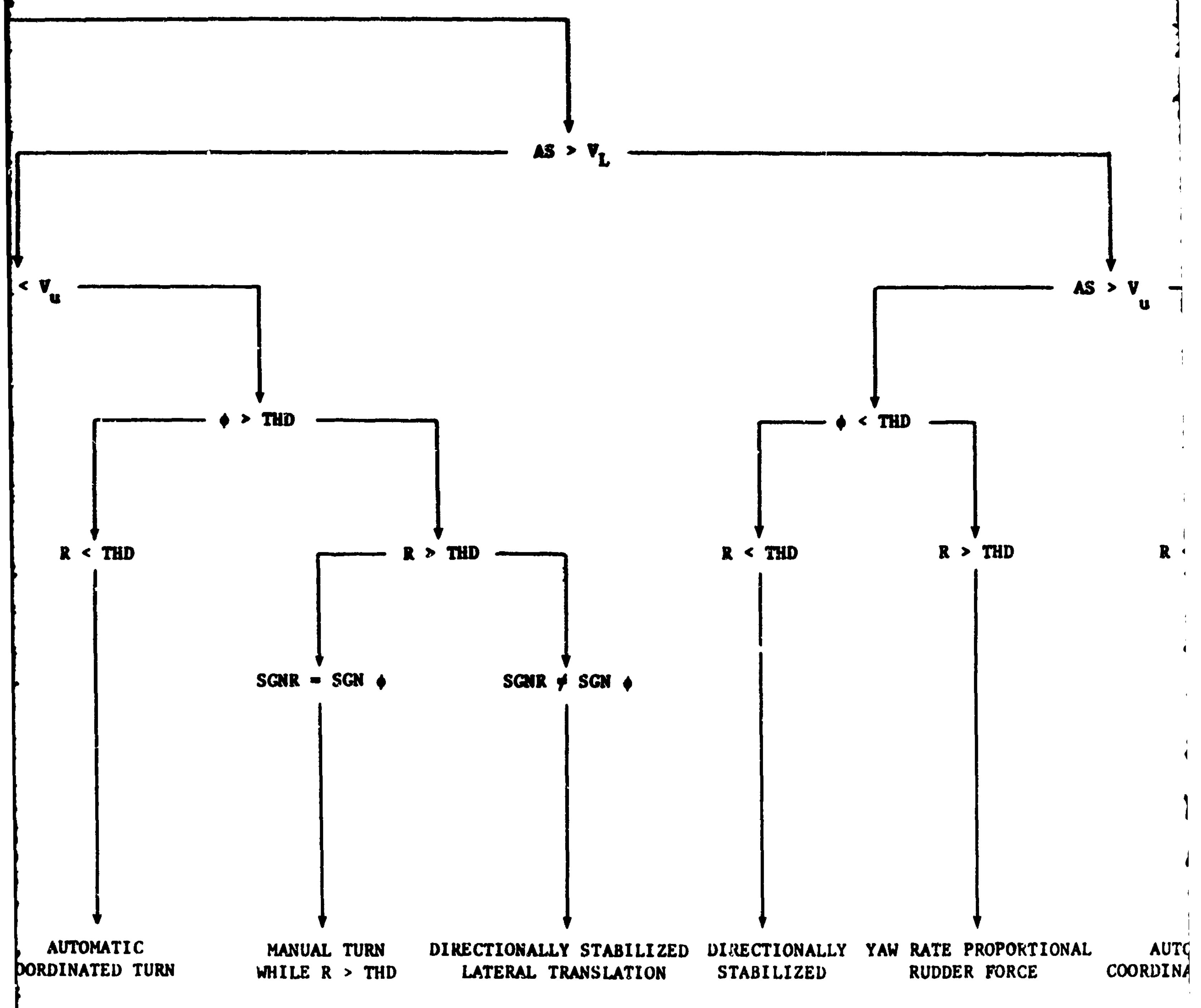

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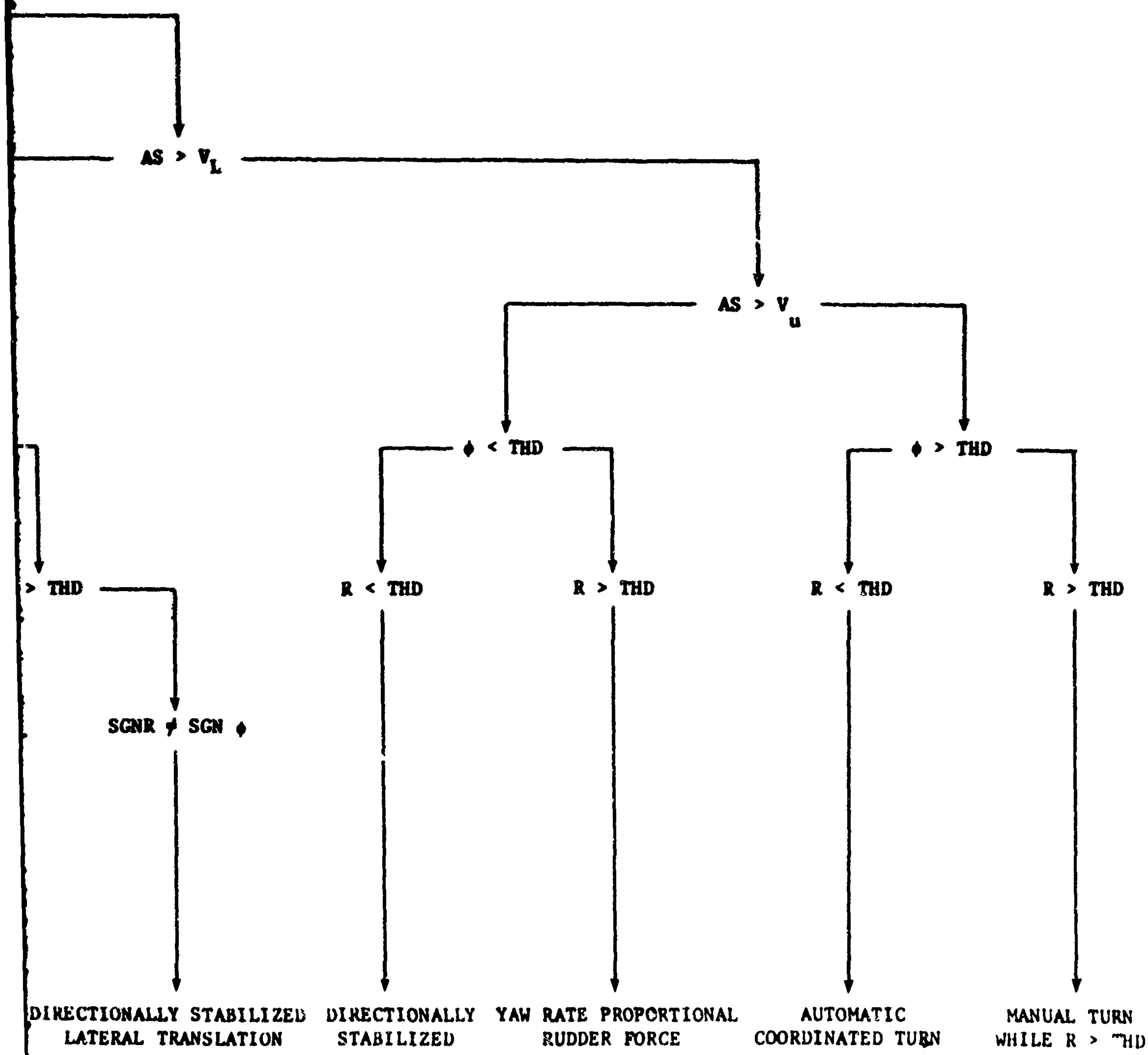
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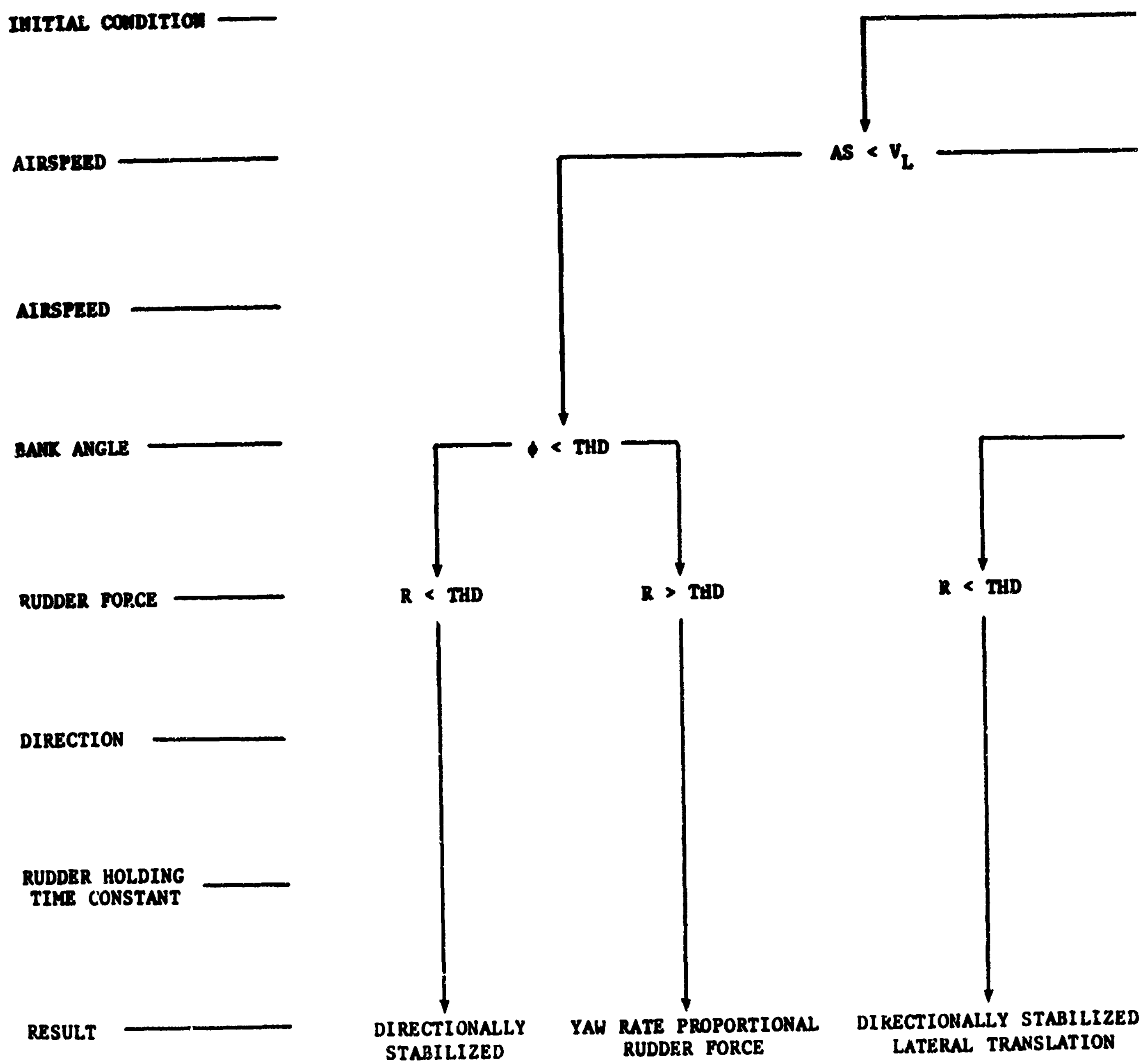
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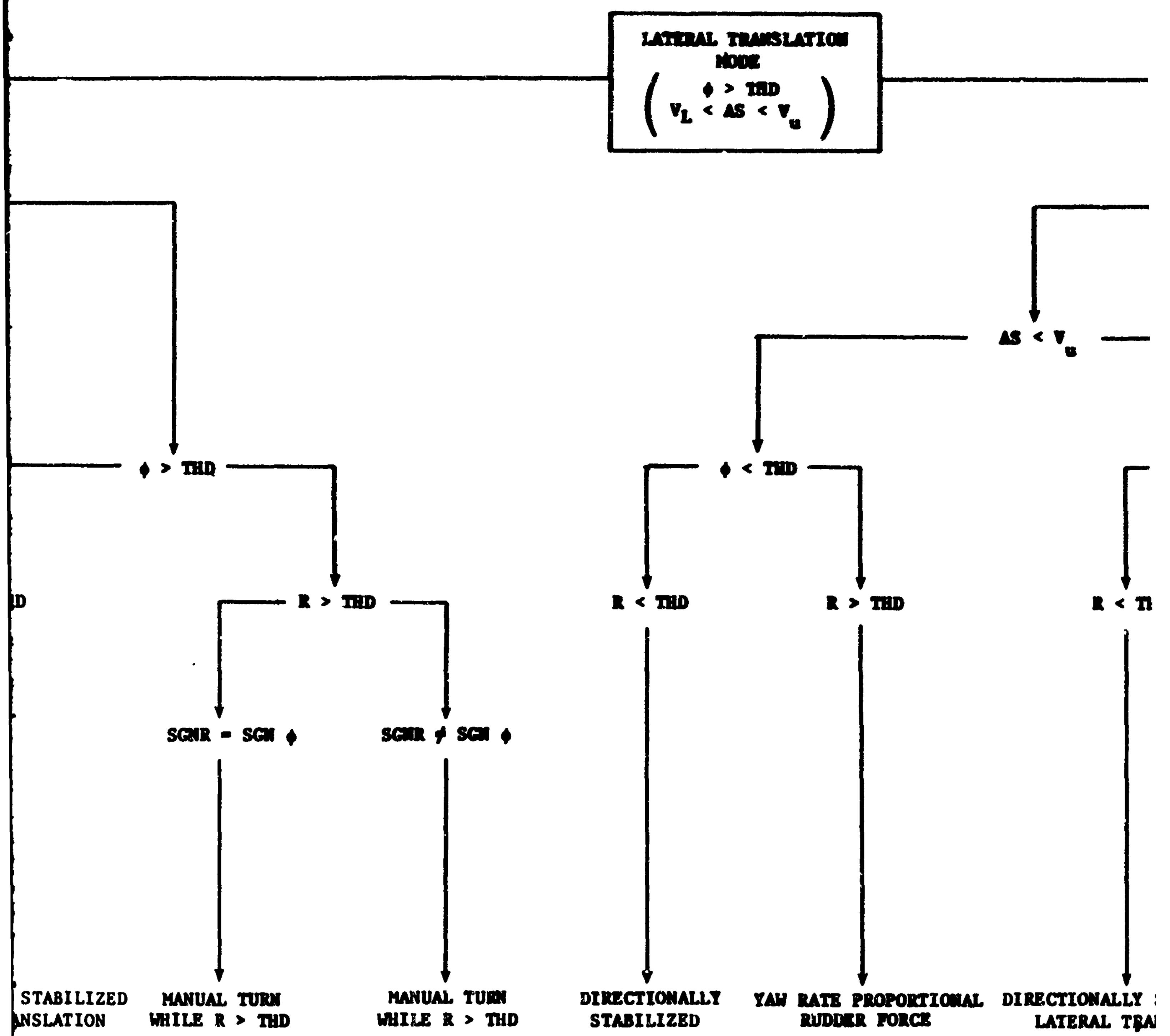

Figure 9. CH-3C, Lateral Translation Mode

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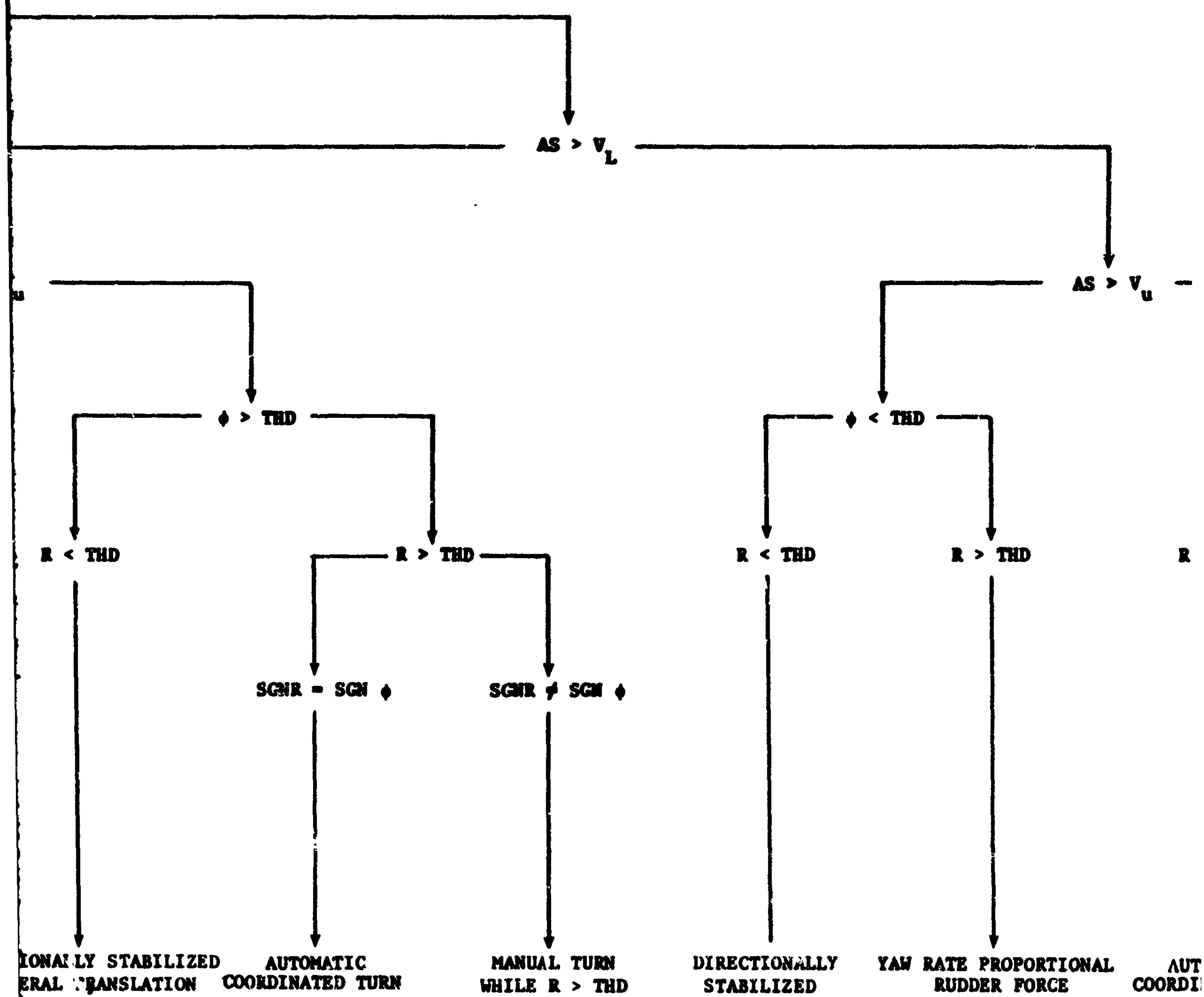
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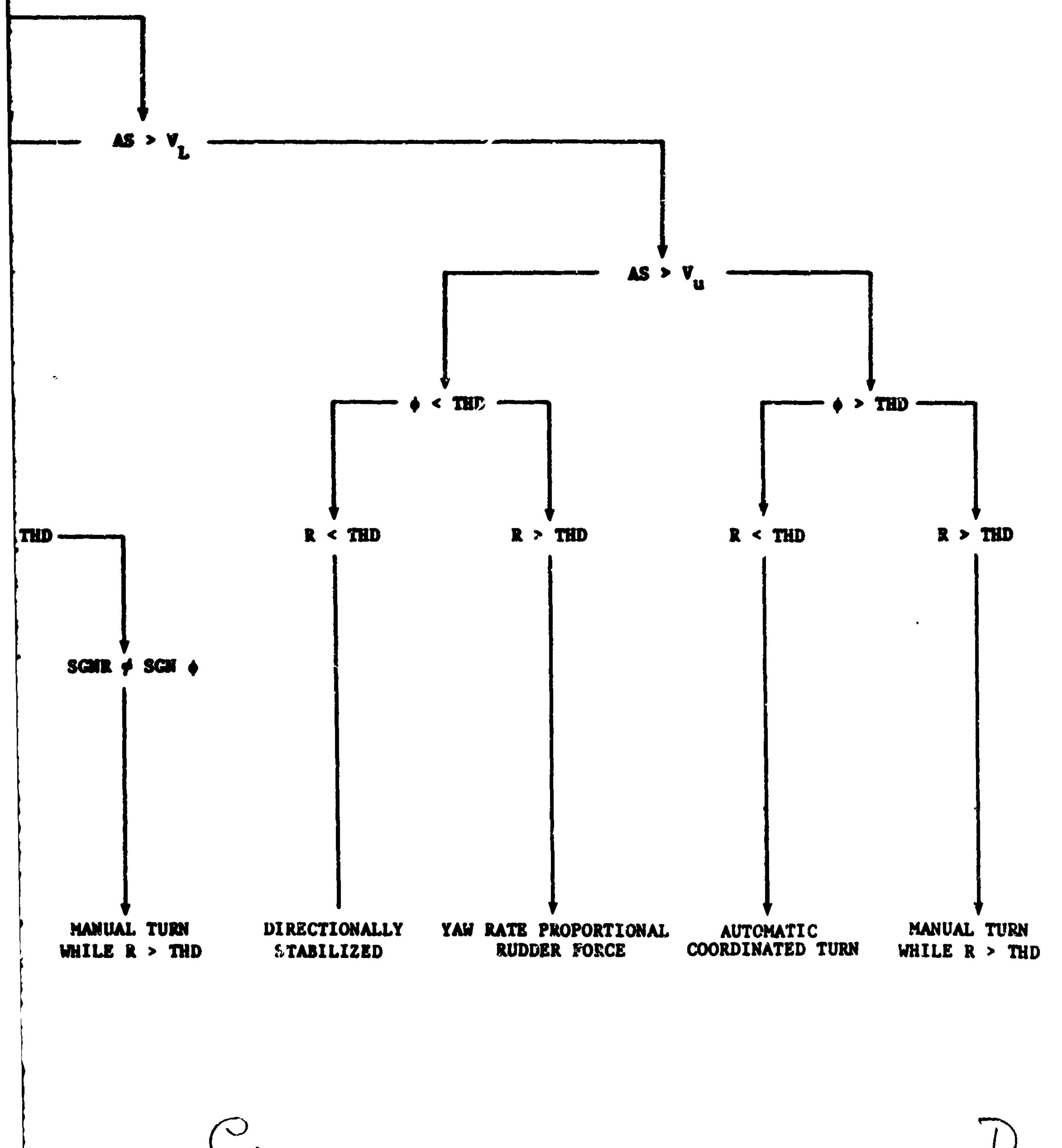
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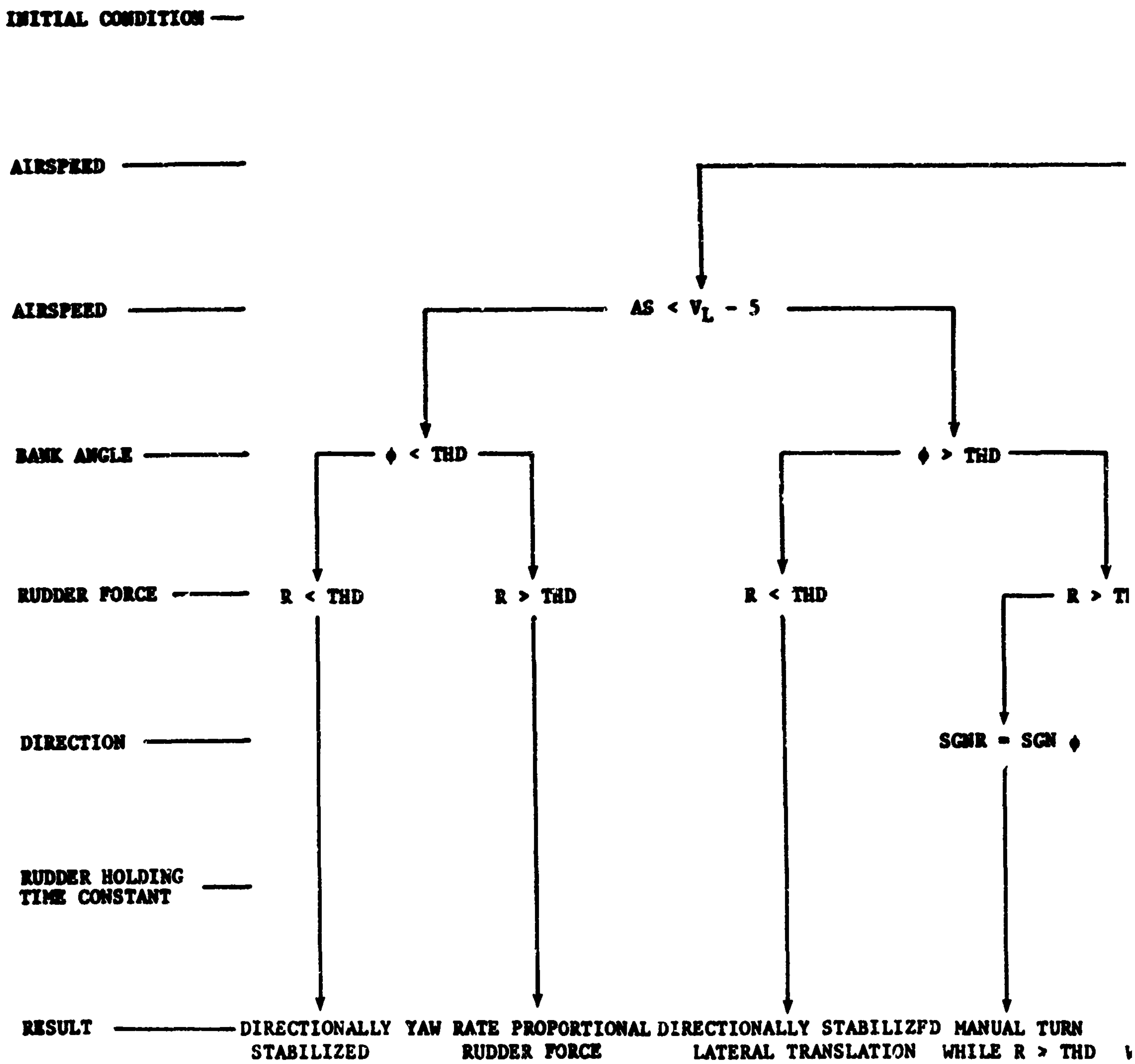
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SGNR = SGN ϕ
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YAW RATE PROPORTIONAL RUDDER FORCE
DIRECTIONALLY STABILIZED LATERAL TRANSLATION
MANUAL TURN WHILE R > THD

A1

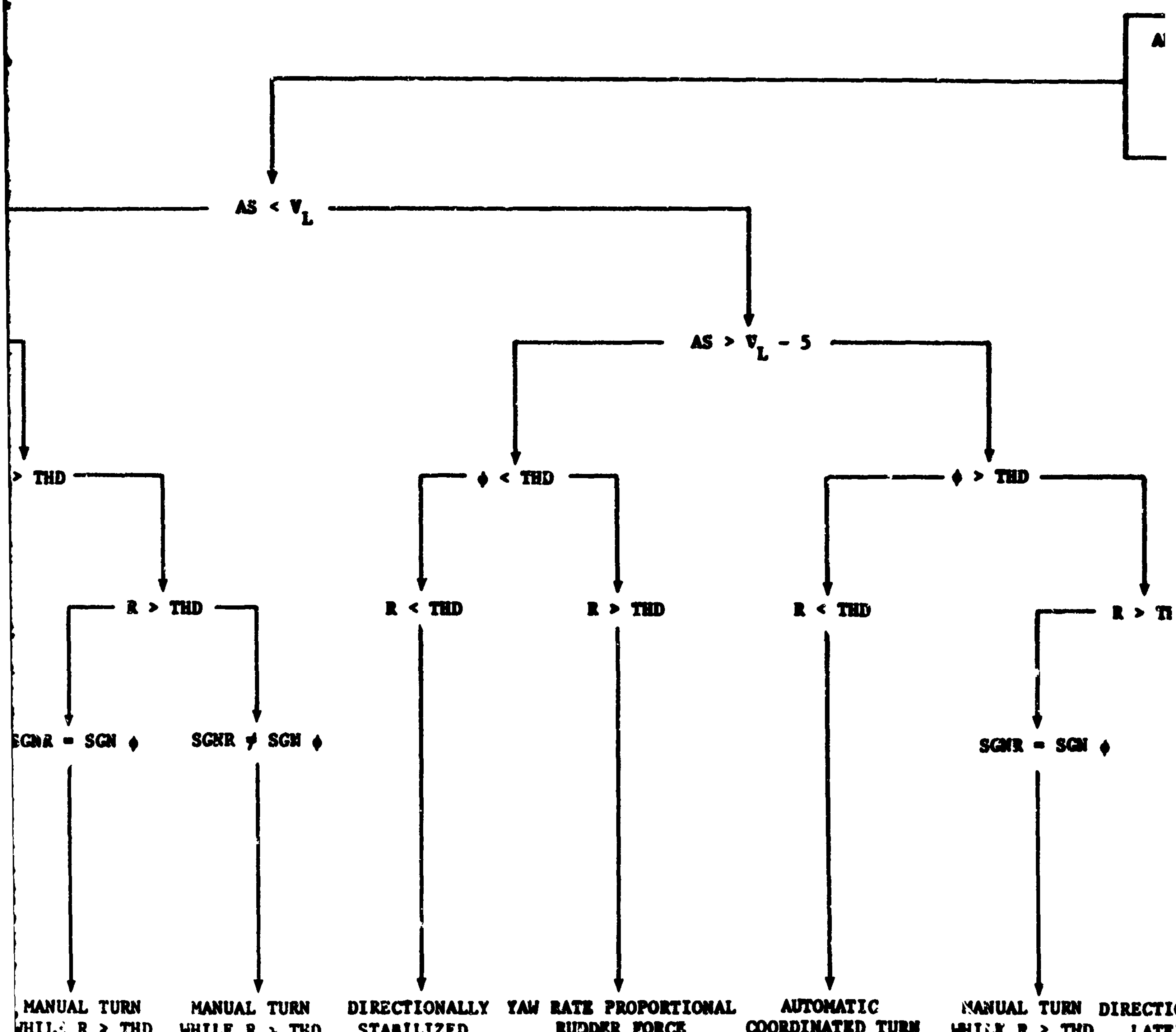


Figure 10. CH-3C,

B

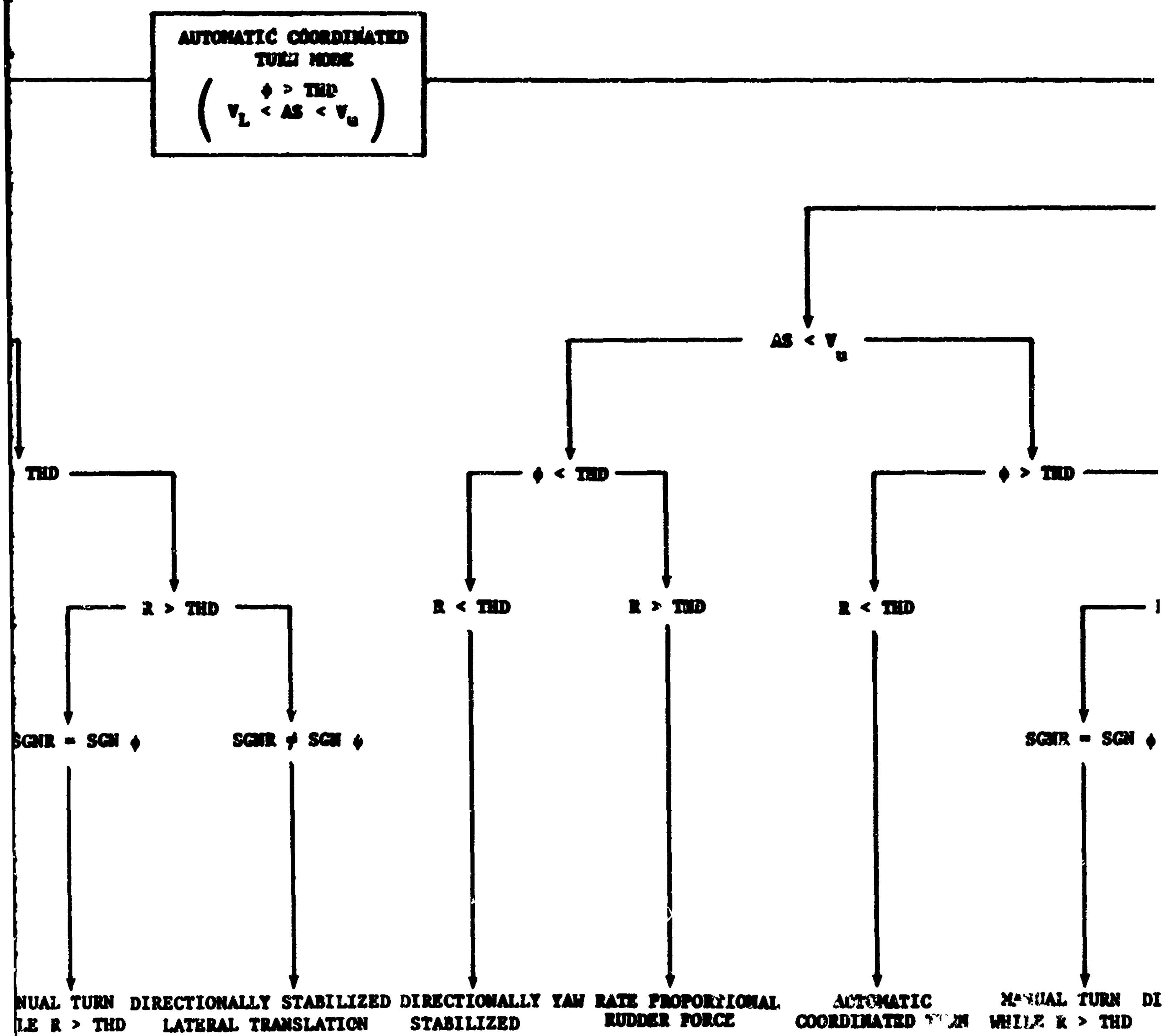
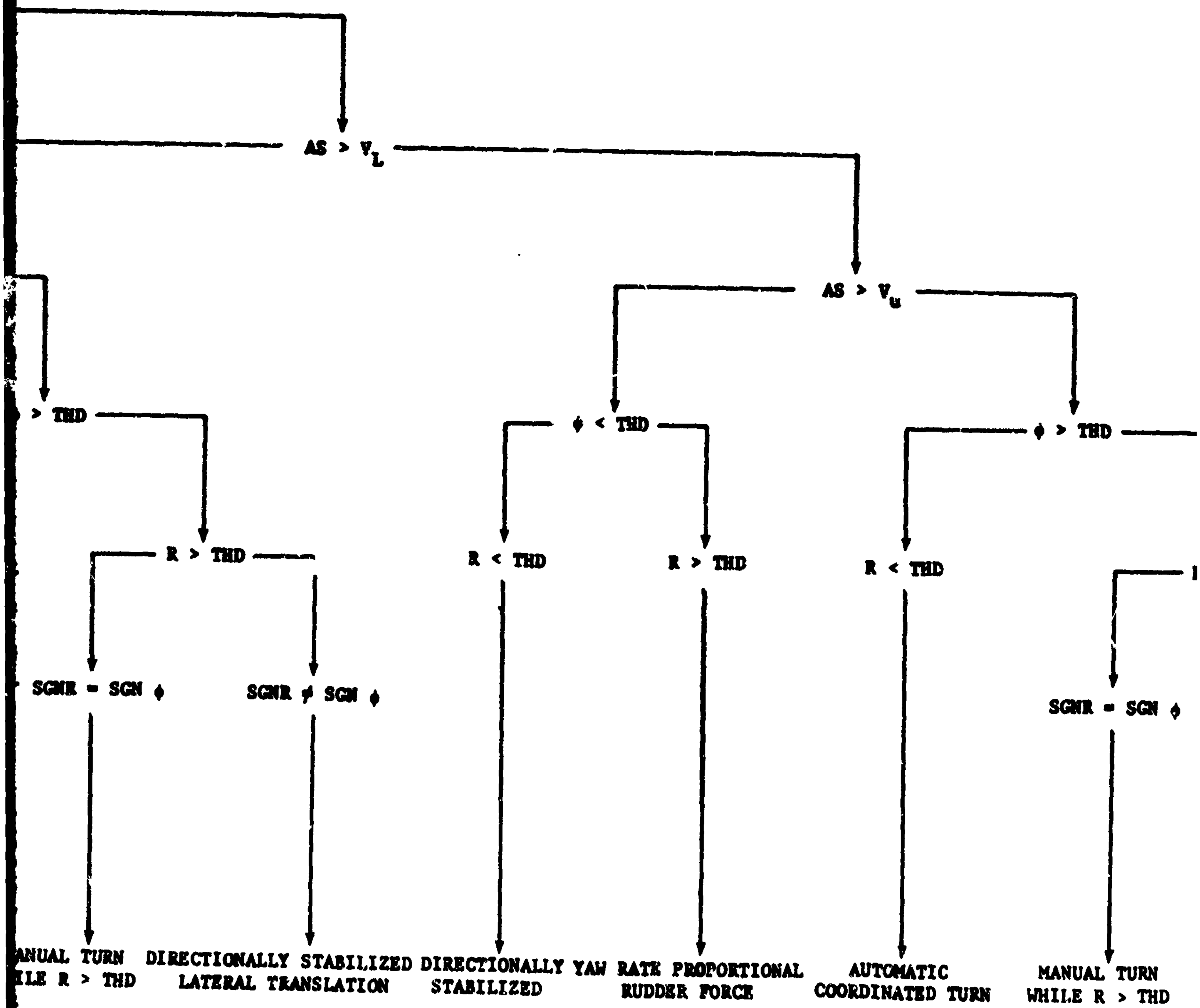


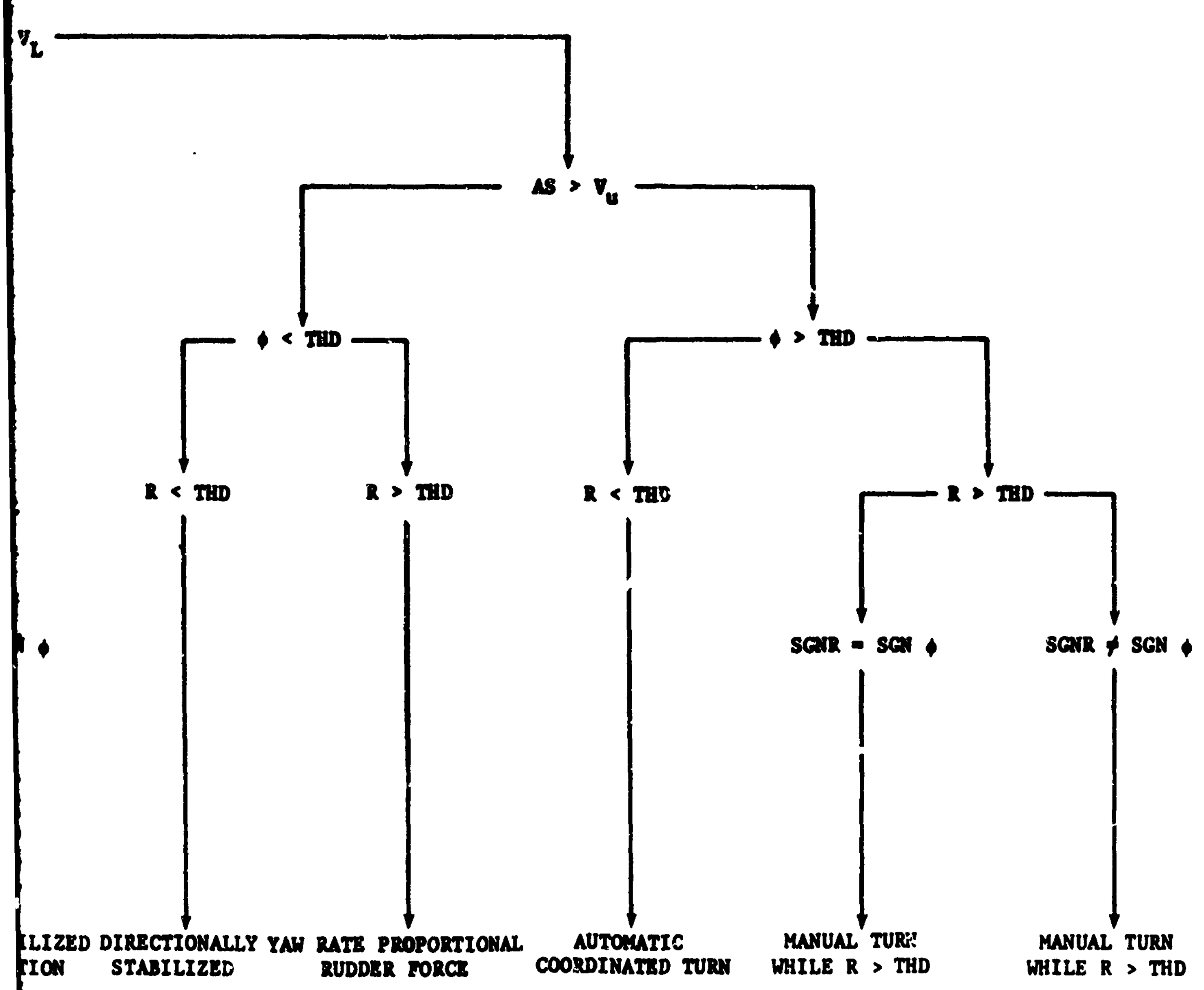
Figure 10. CH-3C, Automatic Coordinated Turn Mode

e.



AS > V_L
AS > V_u
ϕ > THD
ϕ < THD
ϕ > THD
R > THD
R < THD
R > THD
R < THD
SGNR = SGN ϕ
SGNR ≠ SGN ϕ
SGNR = SGN ϕ
ANUAL TURN ILE R > THD
DIRECTIONALLY STABILIZED LATERAL TRANSLATION
DIRECTIONALLY STABILIZED
YAW RATE PROPORTIONAL RUDDER FORCE
AUTOMATIC COORDINATED TURN
MANUAL TURN WHILE R > THD

D.


V_L
AS > V_u
ϕ < THD
ϕ > THD
R < THD
R > THD
R < THD
R > THD
ϕ
SGNR = SGN ϕ
SGNR ≠ SGN ϕ
ILIZED
TION
DIRECTIONALLY STABILIZED
YAW RATE PROPORTIONAL RUDDER FORCE
AUTOMATIC COORDINATED TURN
MANUAL TURN WHILE R > THD
MANUAL TURN WHILE R > THD

D.

E.

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Security Classification

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13. ABSTRACT

An analysis was made of the automatic turn coordination systems installed in the helicopter simulator, the H-300, and the CH-3C helicopters to determine the nature of the differences in mode-switching logic between the three installations. The data was obtained from the cognizant design engineers of each project and summarized in this report. Logic flow diagrams of each of the three systems were constructed to indicate the mode switching resulting from changes in airspeed, attitude, and rudder force application. Comparisons of the diagrams indicate differences in the system mode-switching logic.

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